NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL REPORT

ADDITIVE MANUFACTURING SOLUTIONS IN THE UNITED STATES MARINE CORPS

December 2017

By: **Zachary E. Daugherty**
Andrew J. Heiple

Advisors: **Simona Tick**
Timothy Winn

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2017	**3. REPORT TYPE AND DATES COVERED** MBA professional report	
4. TITLE AND SUBTITLE ADDITIVE MANUFACTURING SOLUTIONS IN THE UNITED STATES MARINE CORPS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Zachary E. Daugherty and Andrew J. Heiple			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This project conducts a cost benefit analysis to systematically examine the relative strengths and weaknesses of the current method of obtaining original equipment manufacturer (OEM) parts by the Marine Corps versus additive manufacturing alternatives. These alternatives include the established method of Extrusion and the emerging technology of continuous liquid interface production (CLIP).

The findings from the cost benefit analysis show a cost advantage for additive manufacturing at the production level with a substantial edge given to CLIP in three of four scenarios examined. Based on our methodology and findings, we recommend that the Marine Corps build a data repository of (blockchained) printable files as quickly as accuracy allows. Once complete, the Marine Corps can continue to use the Fortus 250mc and other previously purchased models. When the repository outgrows the capability of the Fortus machines, it can move to Carbon 3D or a similar technology and expand the capability across the Marine Corps.

14. SUBJECT TERMS 3D Printing, additive manufacturing, Marine Corps, cost benefit analysis, CLIP			**15. NUMBER OF PAGES** 119
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

ADDITIVE MANUFACTURING SOLUTIONS IN THE UNITED STATES MARINE CORPS

Zachary E. Daugherty
Captain, United States Marine Corps
B.A., University of South Carolina 2011

Andrew J. Heiple
Captain, United States Marine Corps
B.A., University of Missouri 2009

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CONTRACT MANAGEMENT

and

MASTER OF BUSINESS ADMINISTRATION

from the

NAVAL POSTGRADUATE SCHOOL
December 2017

Approved by: Dr. Simona Tick

LCDR Timothy Winn

Dr. Rene Rendon
Academic Associate
Graduate School of Business and Public Policy

THIS PAGE INTENTIONALLY LEFT BLANK

ADDITIVE MANUFACTURING SOLUTIONS IN THE UNITED STATES MARINE CORPS

ABSTRACT

This project conducts a cost benefit analysis to systematically examine the relative strengths and weaknesses of the current method of obtaining original equipment manufacturer (OEM) parts by the Marine Corps versus additive manufacturing alternatives. These alternatives include the established method of Extrusion and the emerging technology of continuous liquid interface production (CLIP).

The findings from the cost benefit analysis show a cost advantage for additive manufacturing at the production level with a substantial edge given to CLIP in three of four scenarios examined. Based on our methodology and findings, we recommend that the Marine Corps build a data repository of (blockchained) printable files as quickly as accuracy allows. Once complete, the Marine Corps can continue to use the Fortus 250mc and other previously purchased models. When the repository outgrows the capability of the Fortus machines, it can move to Carbon 3D or a similar technology and expand the capability across the Marine Corps.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-Dimensional
AAR	After Action Reports
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ATP	Advanced Turbo Propeller
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CLIP	Continuous Liquid Interface Production
CLR	Combat Logistics Regiment
CNC	Computer Numerically Controlled
COA	Course of Action
COTS	Commercial Off the Shelf
CRADA	Cooperative Research and Development Agreement
DARPA	Defense Advanced Projects Research Agency
DASF	Due and Status File
DDL	Days Deadlined
DFARS	Defense Federal Acquisition Regulations Supplement
DLA	Defense Logistics Agency
DL	Deadlined
DLP	Digital Light Processing
DLS	Digital Light Synthesis
DOD	Department of Defense
DSIAC	Defense Systems Information Analysis Center
DWG	Drawing (file)
DXF	Drawing Interchange Format
ECU	Environmental Control Unit
EOD	Explosive Ordinance Disposal
EXFAB	Expeditionary Fabrication Trailer
EXMAN	Expeditionary Manufacturing Trailer
FAR	Federal Acquisition Regulations
FEDLOG	Federal Logistics Data
FOB	Forward Operating Base
FSR	Field Service Representatives
GABF	General Accounts Balance File
GAO	Government Accountability Office
GCSS	Global Combat Support System

GE	General Electric
HQMC	Headquarters Marine Corps
I&L	Installations and Logistics
ILI	Intelligent Liquid Interface
IP	Intellectual Property
ISO	International Organization for Standardization
JIT	Just In Time
LPTA	Lowest Price Technically Acceptable
LVSR	Logistics Vehicle System Replacement
Maradmin	Marine Administrative Message
MCSC	Marine Corps Systems Command
MARES	Marine Corps Automated Readiness Evaluation System
M-ATV	Mine Resistant Ambush Protected All-Terrain Vehicle
MCBul	Marine Corps Bulletin
MCCLL	Marine Corps Center for Lessons Learned
MCSC	Marine Corps Systems Command
MEE	Mission Essential Equipment
MET	Mission Essential Task
MEU	Marine Expeditionary Unit
MICE	Mesoscale Integrated Conformal Electronics
MOS	Military Occupational Specialty
MRAP	Mine Resistant Ambush Protected (Vehicle)
NPV	Net Present Value
NSN	National Stock Number
OEM	Original Equipment Manufacturer
PEI	Principal End Item
R4OG	Redeployment and Retrograde in support of Reset and Reconstitution Operations Group
ROMO	Range of Military Operations
RPU	Rigid Polyurethane
SASC	Senate Armed Service Committee
SEMS	Shop Equipment Machine Shop
SESAM	The Society in Europe for Simulation Applied to Medicine
SLA	Stereolithography
SLS	Selective Laser Sintering

SMU	Supply Management Unit
SNCO	Staff Non-Commissioned Officer
SOP	Standard Operating Procedure
SPAWAR	Space and Naval Warfare Systems Command
TAMCN	Table of Authorized Material Control Number
TFSMS	Total Force Structure Management System
TLCM-OST	Total Life Cycle Management- Operational Support Tool
TO/E	Table of Organization and Equipment
TQ	Al-Taqaddum Air Base
TTP	Tactics, Techniques, and Procedures
UAS	Unmanned Aerial Systems
UMMIPS	Uniform Material Movement and Issue Priority System
USD	AT&L Under Secretary of Defense for Acquisition, Technology, and Logistics
USMC	United States Marine Corps
UV	Ultra-Violet (Light)
VTOL	Vertical Take-off and Landing
WEBFLIS	Web Federal Logistics Information System
WIPO	World Intellectual Property Organization

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First and foremost, we would like to thank God for the blessings and opportunity to serve. This thesis would not have been possible without the tremendous support of our family, friends, advisors, and fellow Marines. To Amanda and Misty, thank you for your support in balancing work and family, allowing us to focus for hours on this project. To Nathan, Karen, Gabriel, and Brandon, we know you wanted more time to play; so did we. To Dr. Simona Tick and LCDR Timothy Winn, thank you for your perseverance and advice as you read through draft after draft. Your guidance was instrumental in completing this process. To everyone else, thank you for taking time out of your very busy schedules to answer questions and provide guidance. Your assistance and expertise were invaluable. This was a rewarding experience for both of us, and hopefully, our contribution to the field will be useful for the Marine Corps.

We would like to thank the Marines and civilians who directly contributed to this analysis:

LtCol Donald Harlow (USMC)	LtCol Gregory Pace (USMC)
LtCol Dane Salm (USMC)	Major Timothy Fretwell (USMC)
Major Aaron Glover (USMC)	Capt. Chris Wood (USMC)
Capt. Alvaro Yanes	CWO4 Oscar Gonzales (USMC)
CWO2 Daniel Bower (USMC)	GySgt Travis Arndt (USMC)
GySgt Justin Horn (USMC)	GySgt Joshua Weaver (USMC)
SSgt Wesley Jones (USMC)	Dr. Kristen Holzworth (SPAWAR)
John Rolland (U.S. Army Ret., Carbon 3D)	Mr. Phil DeSimone (Carbon 3D)

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Additive manufacturing (AM) is synonymous with three-dimensional (3D) printing. These terms are interchangeable within industry. In its simplest form, additive manufacturing is the creation of an item by adding layers of a material to form the item. This is different than the traditional process of subtractive manufacturing, which removes excess material to produce an item. Subtractive manufacturing creates significant waste in terms of raw materials. The cut away material does not add value to the end item but requires resources for transport and storage. Alternatively, additive manufacturing offers increased flexibility for production at the point of need with greatly reduced waste. The flexibility manifests through speed of production and reduced logistical stocking requirements. Properly harnessing this technology promises a future of true “just in time” (JIT) logistics.

A. OBJECTIVES

The purpose of this analysis is to compare the current method of obtaining original equipment manufacturer (OEM) parts via the supply system to available additive manufacturing alternatives to reduce costs and expedite the replacement of parts. These alternatives include the currently utilized method of Extrusion printing and the emerging technology of continuous liquid interface production (CLIP). The following are the specific research questions addressed by this thesis:

- Is additive manufacturing a cost reducing option for the Marine Corps, compared to acquiring OEM items from the established supply chain?
- Among the additive manufacturing alternatives, is it more cost efficient for the Marine Corps to use Extrusion or CLIP?

B. IMPACT

This project develops a decision-support model that the Marine Corps can utilize to evaluate future additive manufacturing expansion. While currently limited, the available data regarding additive manufacturing in the Marine Corps is expanding continuously. The accuracy of cost-benefit analysis (CBA) for these technologies will continue to increase as more data becomes available. The Marine Corps is currently exploring the applicability of this technology through a series of innovation initiatives and test-bed units. As the limits of the applicability expand, the Marine Corps will transition to a more production-based approach with additive manufacturing. We estimate that this shift will likely occur in the next decade. To date, the Marine Corps invested more than $500,000 in additive manufacturing (D. Bower, personal communication, September 21, 2017). By leveraging the predictive model developed within this CBA, the Marine Corps can increase cost efficiency in future additive manufacturing acquisitions.

C. METHOD

This CBA captures and analyzes relevant data gathered from open sources and direct communications with the Marine Corps and Carbon 3D, an American additive manufacturing company. This recently gathered data is extremely applicable as it accurately addresses the Marine Corps' current position regarding additive manufacturing. The field of additive manufacturing is constantly evolving, and pricing information loses relevancy quickly. This analysis monetizes costs and benefits, adjusts for inflation, and compares net present values in 2017 dollars in a systematic examination of the strengths and weaknesses of the current supply chain and 3D printing alternatives. Coupled with sensitivity analysis, the model developed in this project provides functional decision-making support, which easily adjusts to include newly available data. The sensitivity analyses include baseline analysis, sensitivity of results to valuation of time, sensitivity to estimated days deadlined, and sensitivity to initial investment. The "Methodology" chapter details the CBA steps. Of note, the valuation of time is particularly sensitive, and the "Methodology" chapter covers in depth the rationale followed in this study.

D. ORGANIZATION OF STUDY

The structure of this study provides a reader with no experience in additive manufacturing all the tools required to make accurate additive manufacturing acquisition decisions. The remainder of this thesis is divided into five chapters. The "Background" chapter provides a brief history of additive manufacturing and a short description on the basic types of additive manufacturing. The “Background” chapter also includes industry and Marine Corps technological milestones relevant to this study. The “Literature Review” is broken into three sections, detailing scholarly articles, books, and directives related to additive manufacturing in the following three areas industry, Department of Defense (DOD), and the Marine Corps. The “Methodology” chapter outlines the steps used to conduct the CBA, describes in detail the technical data gathered, and the valuation of time methodology. The “Cost-Benefit Analysis” chapter provides the reader with the baseline analysis and three sensitivity analyses used to validate the findings. The “Conclusion” chapter summarizes the findings, provides recommendations, and details suggested future research.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. INTRODUCTION TO ADDITIVE MANUFACTURING

In 1986, Chuck Hull invented a process called stereolithography. This was the first form of high-technology additive manufacturing, as opposed to low-tech processes such as layering clay to make pots, or building layers of fiberglass for manufacturing automobiles. The invention of stereolithography led to the development and founding of 3D Systems, a publicly traded company headquartered in North Carolina. This technology, initially identified as rapid-prototyping, created one-off models and proof of concept items (Grimm, 2004). Additive manufacturing technology rapidly expanded with new processes, sustaining an average growth rate of 57% a year for the period of 1988 to 1997 (Grimm, 2004). According to the *Wohlers Report*, the total manufacturing industry is $12.8 trillion annually (Wohlers, Campbell, Diegel, Kowen, & Caffrey, 2017). Currently, additive manufacturing only accounts for an estimated 0.047% of the industry, representing $6.1 billion in total production. It took 20 years (1986–2006) for additive manufacturing to account for $1 billion in total production. In the next six years (2007-2013), additive manufacturing expanded to $2 billion. After 2013, additive manufacturing has increased steadily at a rate of $1 billion per year. Future projections conservatively estimate that additive manufacturing will grow to over 5% of total manufacturing resulting in a $640 billion industry (Wohlers et al., 2017).

B. TYPES OF ADDITIVE MANUFACTURING

There is no set industry standard to define the different types of additive manufacturing. Some experts will cite nine types, others will definitively name seven categories, and still others will report there are only six. The *Wohlers Report* is the industry standard we chose to utilize, and they outline seven distinct types of additive manufacturing: “material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion, and directed energy deposition” (Wohlers et al., 2017, p. 34). An understanding of the currently available technologies is paramount when considering efficiencies gained or lost by selecting a printing method.

1. Material Extrusion

Material Extrusion first appeared in 1991, introduced by a Minnesota-based company called Stratasys (Wohlers et al., 2017). It is the method that comes to mind when most people think about 3D printing. This method was the first to be available for home use and spawned the Maker Movement. According to the *Wohlers Report*, "compared to other AM processes material Extrusion systems are often a less expensive alternative and relatively easy to operate" (Wohlers et al., 2017, p. 35). Material Extrusion, is a process in which filament is melted to a semi-liquid form, and placed drop by drop over an *X*- and *Y*-axis. Once a single layer is complete the build platform will lower, or the printing head will raise on the *Z*-axis, to allow printing on the next level. Figure 1 provides a graphical representation of this process. The most common material for a filament is acrylonitrile butadiene styrene (ABS). However, other materials include "ceramics, composites, metal-filled clays, concrete, food, and living cells" (Wohlers et al., 2017, p. 35). The material Extrusion method uses print materials in two main ways. The material acts as either build material or support material. Depending on the machine, additional print heads offer the capacity to load multiple materials.

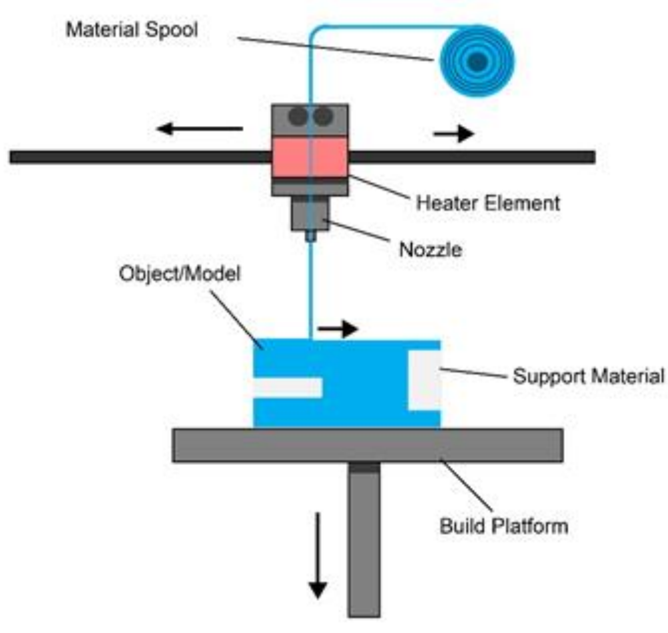


Figure 1. Material Extrusion. Source: Loughborough University (2017c).

2. Material Jetting

The Defense Advanced Research Projects Agency (DARPA) first pioneered material jetting in pursuit of the ability to print integrated electronics (Wohlers et al., 2017). The first occurrence was the DARPA project Mesoscale Integrated Conformal Electronics (MICE). DARPA's MICE resulted in the development of the aerosol jet that was a key element enabling this segment of additive manufacturing (Optomec, 2017). Material jetting works in a similar fashion to an inkjet printer, where the materials dispense in liquid droplets as the print head moves around the build platform. Figure 2 depicts this process. The most basic machines utilize a single print head, while more complex models utilize multiple heads simultaneously, each dispensing a different material. This allows the creation of complex designs with versatile properties and material composition. The majority of these applications require a UV light to harden the printed material, with the notable exception of direct-write technology, which deposits functional inks that do not require hardening. The primary limitation of direct write is the inability to print beyond two and a half dimensions, meaning a two dimensional print that can curve around corners (Wohlers et al., 2017).

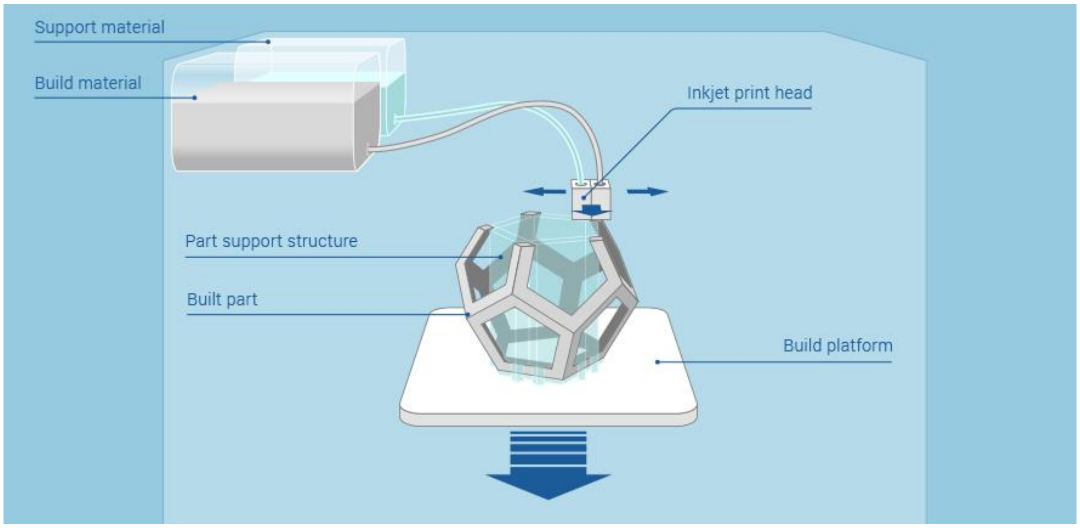


Figure 2. Material Jetting. Source: Additively Ltd (n.d.).

3. Binder Jetting

There are two materials used in binder jetting, liquid adhesive and a powder. The liquid adhesive dispenses with inkjet print head nozzles and acts to coalesce the powder within the powder bed (Wohlers et al., 2017). The dry powder acts as the build material, and interacts with the liquid adhesive to form solid objects. Similar to other methods previously discussed, the print head moves along an *X*- and *Y*-axis and the build platform lowers level by level, as shown in Figure 3. This is a comparatively slow method of printing and requires extensive finishing work (Loughborough University, 2017a).

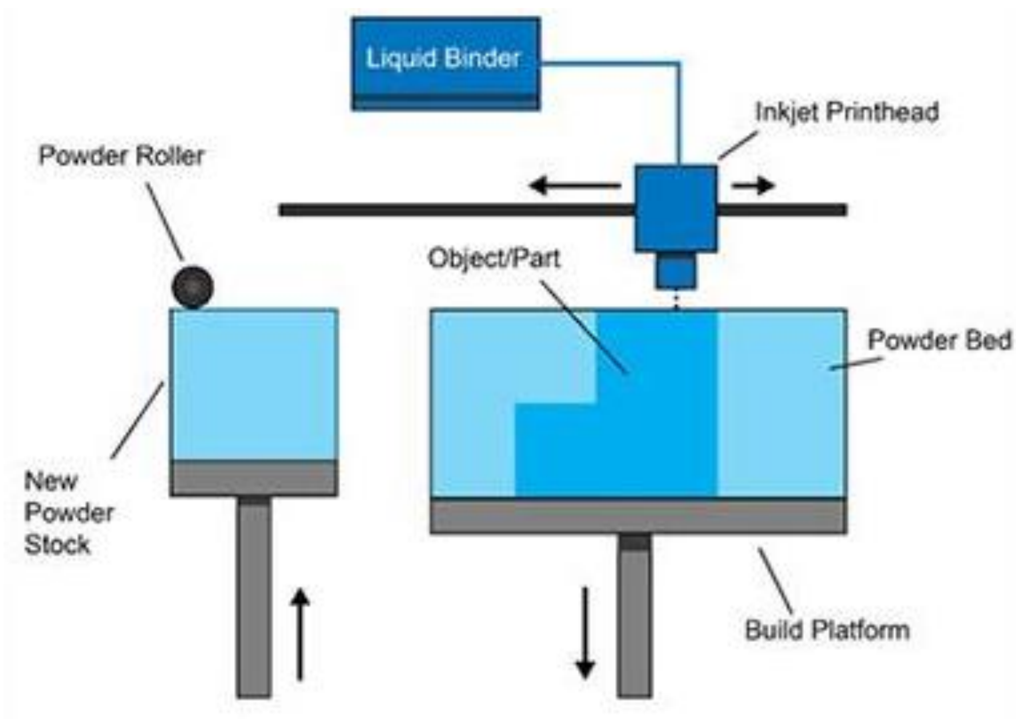


Figure 3. Binder Jetting. Source: Loughborough University (2017a).

4. Sheet Lamination

Sheet lamination is similar to the making of plywood, where thin layers are adhered to one another to form a solid and more structurally sound whole. With this process, a single layer cuts, and another layer adds and adheres to the original. There are different methods for adhering the next layer. Early models used thin paper with one side pre-coated using an adhesive. More current methods use metal and ultra-sonic welding to adhere the next layer, or utilize print heads that selectively apply adhesive. Figure 4 demonstrates this process. A laser or a blade then cuts each layer to shape the final product. Wohlers (2017) states that "the cost of material is among the lowest in the industry, although it does produce considerable waste" (p. 39). Sheet lamination products are generally not preferred for structural use. However, when using sheet lamination, it is possible to create specific internal geometries (Loughborough University, 2017e).

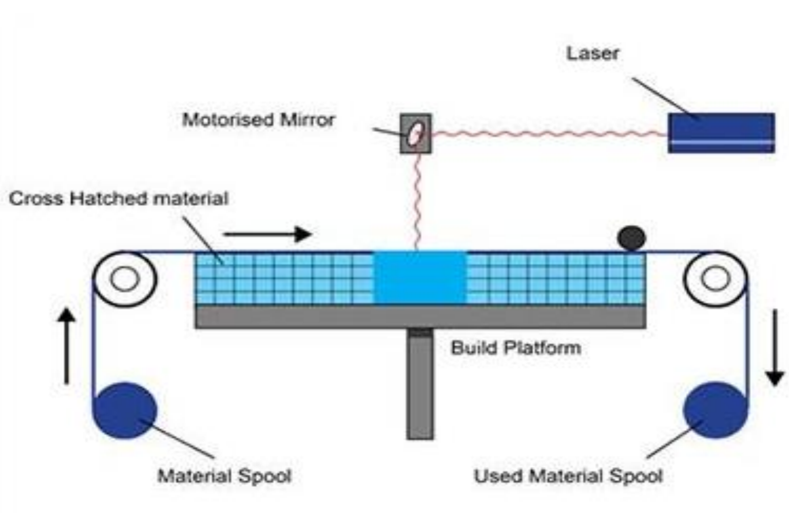


Figure 4. Sheet Lamination. Source: Loughborough University (2017e).

5. Vat Photopolymerization

During the vat photopolymerization process, the introduction of ultraviolet light hardens a container, build tray, or vat of photosensitive resin layer by layer. Chuck Hull invented the first form of vat photopolymerization (stereolithography) in 1986. For some forms of vat photopolymerization, the light comes from above using a laser and series of mirrors. With a digital light processing (DLP) approach, the product builds vertically and continuously by exposing the bottom of the liquid to light. This is process is shown in Figure 5. This has the advantage of requiring a smaller amount of resin when compared to more traditional ultraviolet vat photopolymerization approaches (Wohlers et al., 2017).

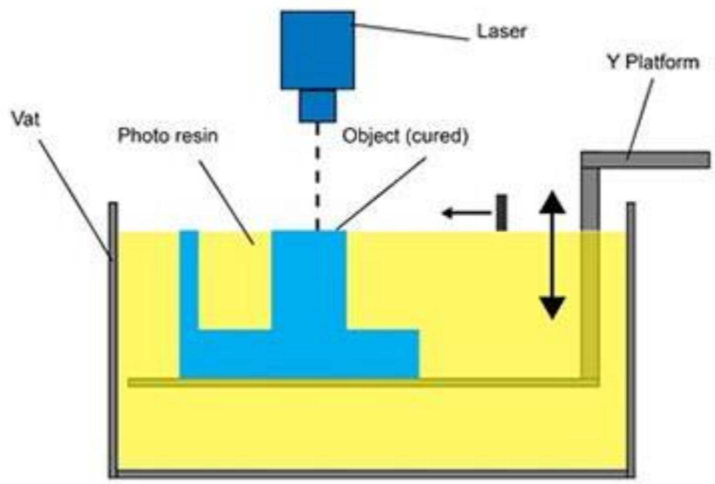


Figure 5. Vat Photopolymerization. Source: Loughborough University (2017f).

Carbon 3D, a privately owned company in California, introduced CLIP in March 2015 (Wohlers et al., 2017). They generated market enthusiasm using trade shows and TED Talks to demonstrate their ability to print a geodesic sphere in six minutes. The shape was sufficiently complex that reproduction is not possible using subtractive manufacturing. The company claims to be able to print 75 to 100 times faster than standard Extrusion printing (also referred to as the material Extrusion method). The following is Carbon 3D’s explanation of its process:

> Despite industry advances, traditional approaches to additive manufacturing force trade-offs between surface finish and mechanical properties. In contrast, DLS (Digital Light Synthesis) enabled by Carbon's proprietary CLIP technology, is a breakthrough process that uses digital light projection, oxygen permeable optics, and programmable liquid resins to produce parts with excellent mechanical properties, resolution, and surface finish. (Carbon 3D, n.d., p. 1)

Figure 6 depicts the process described by Carbon 3D. There are multiple drawbacks to the CLIP method of 3D printing. First, they are limited in terms of build size by the dimensions of their oxygen permeable glass, which creates the requisite dead-zone. Additionally, the resin is more expensive than other build materials, and the shelf-life is notoriously short once opened and introduced to the printer; generally, less than 12 hours (J. Rolland, personal communication, September 14, 2017). Carbon 3D requires all of their printers to be connected to their network to initialize a print order. Due to the inherent properties of the liquid resin, Carbon 3D printers require a level and stable environment. These printers also require extensive leveling if moved. This presents a significant hurdle when contemplating deployed application, and may offset some of the efficiency gained through decreased print times.

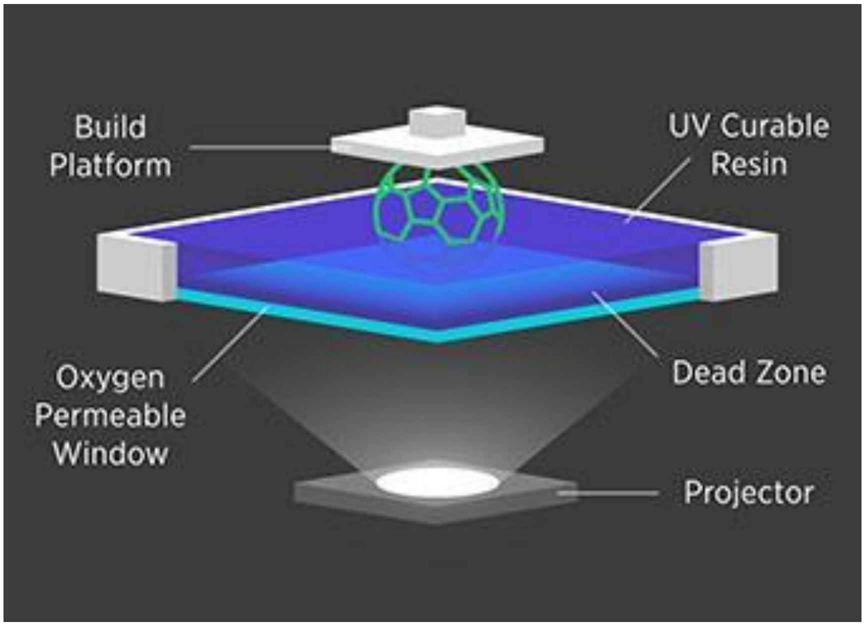


Figure 6. Continuous Liquid Interface Production. Source: Crawford (2016).

NewPro3D, a Canadian company, was not included in the list of companies examined by the *Wohlers Report* in 2017. As a result, the only reliable information available is from its website and third-party reviews of their products. The company utilizes a printing technology called intelligent liquid interface (ILI). NewPro3D is similar to Carbon 3D in terms of methodology and reported printing speeds. However, they are technologically different in terms of how they create their oxygen dead-zone during the printing process. Carbon 3D uses oxygen permeable glass, whereas NewPro3D utilizes a wettable membrane, as shown in Figure 7. According to NewPro3D, this method has no print size restrictions. NewPro3D has released videos demonstrating their printers printing the same geodesic sphere as Carbon 3D for their marketing efforts. Their website cites the print times for the sphere across different printing methods. Utilizing their ILI, it takes four and a half minutes to print the item, while stereolithography (SLA) takes 690 minutes (NewPro3D, 2016a).

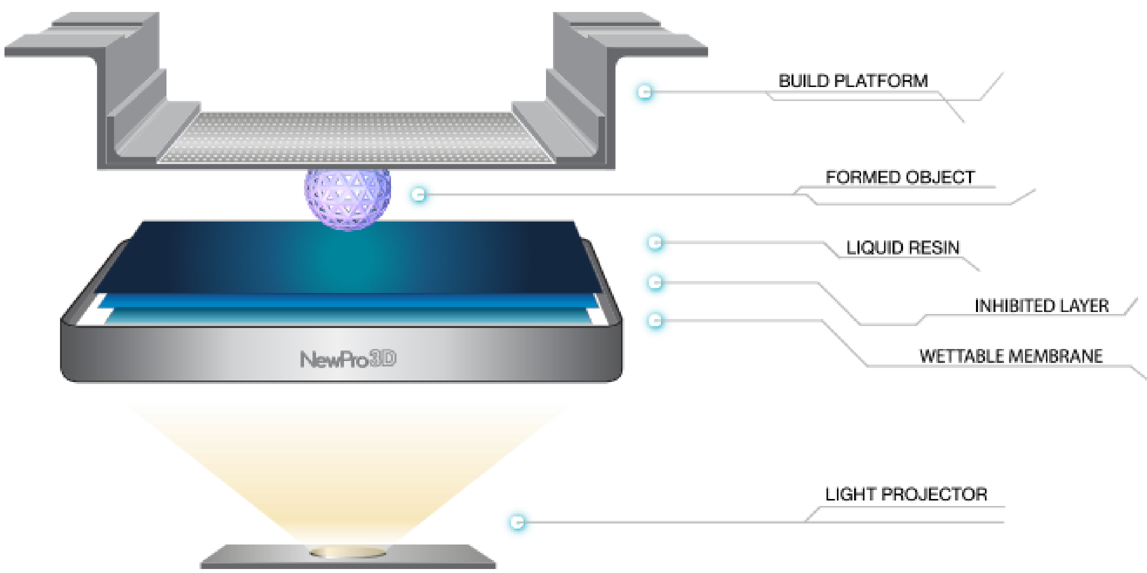


Figure 7. Intelligent Liquid Interface. Source: NewPro3D (2016b).

6. Powder Bed Fusion

Powder bed fusion is similar to binder jetting; both methods utilize a powder bed as the build material. The difference is that in powder bed fusion the adhesion source is heat in the form or a laser or electron beam. The powder is re-applied layer by layer as the heat source moves along an *X*-axis and *Y*-axis to solidify the build material, as demonstrated n Figure 8. There is a cumulative degradation due to the proximity of the unhardened powder to the continual heat, resulting in a limited number of uses. The continuous addition of new powder between builds is necessary to counteract this. The powder bed material can be composed of plastics, metals, or foundry sand (Wohlers et al., 2017). Comparatively, powder bed fusion has one of the higher associated costs found in additive manufacturing. These costs originate from safety requirements, stemming from the gas used to heat the powder. Additionally, the recycling costs for properly disposing of used powder drives up the total expense. For these reasons, powder bed fusion primarily creates finished products once the testing and prototyping is complete (Wohlers et al., 2017).

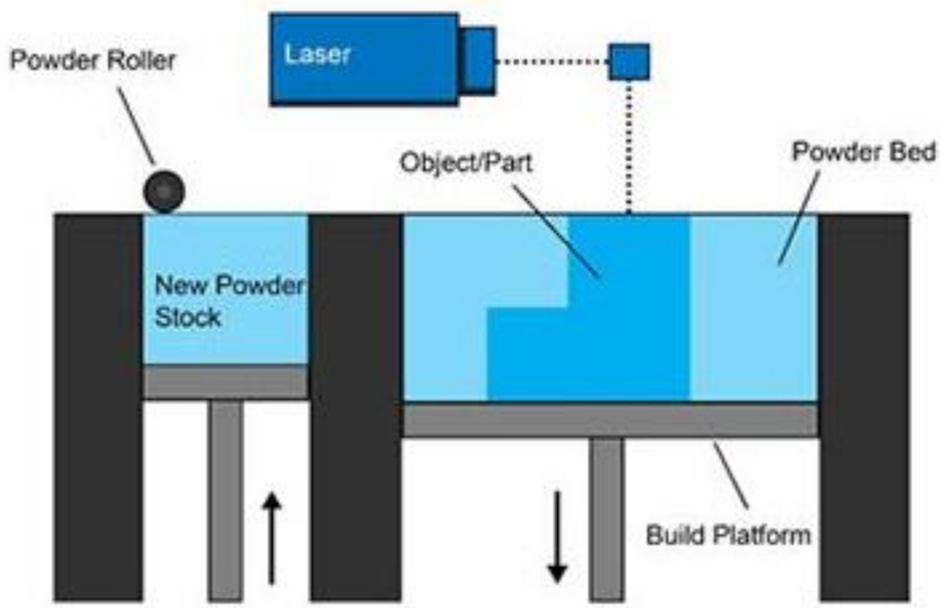


Figure 8. Powder Bed Fusion. Source: Loughborough University (2017d).

7. Directed Energy Deposition

Directed energy deposition is fundamentally different from the other methods discussed thus far. This method adds material to a previously existing object. There are two main components to directed energy deposition: build material and heat source. The build material can be metal, plastic, or ceramic, though the medium most commonly used is metal. This build material enables application from a variety of positions, and the nozzle that applies the build material can rotate across multiple axes. The heat source is generally a laser; however, any focused heat source is effective if properly utilized. A less common but currently expanding heat source is the electron beam. This technology has been widely integrated with traditional computer numerically controlled (CNC) machines as a way of adding to an existing item, as depicted in Figure 9 (Wohlers et al., 2017; Loughborough University, 2017b).

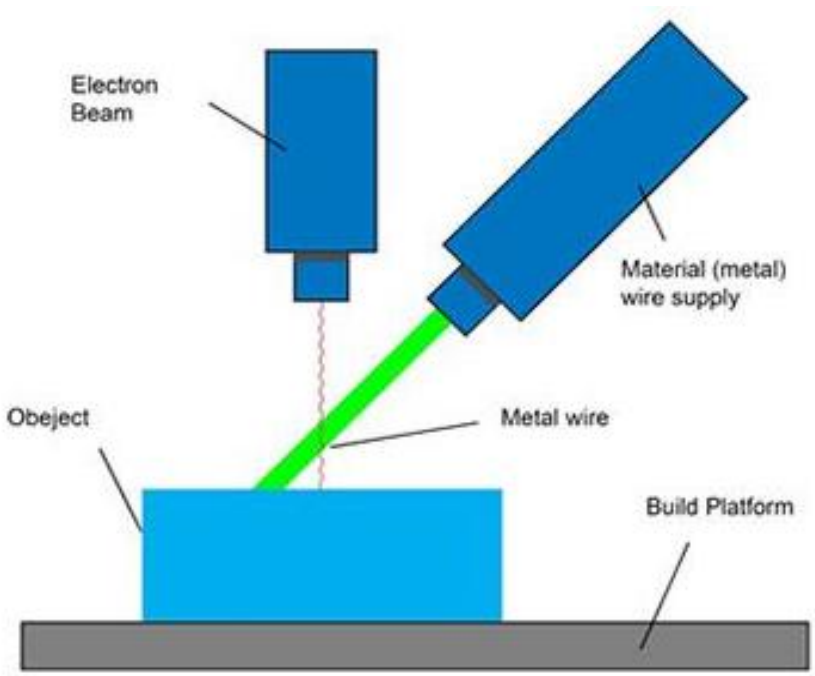


Figure 9. Directed Energy Deposition. Source: Loughborough University (2017b).

C. CURRENT EVENTS

Three-dimensional printing is a rapidly expanding field with new technologies and exaptation occurring with seeming regularity. These advances occur across all disciplines, although this section focuses on recent medical and manufacturing advances in order to highlight the innovative applications that are becoming possible.

1. Spine Mentor Simulator

The 23rd annual meeting of The Society in Europe for Simulation Applied to Medicine (SESAM) occurred June 14–16, 2017. 3D Systems released its Spine Mentor at the conference. The Spine Mentor's primary market is pain medicine surgeons, anesthesiologists, and orthopedic surgeons (3D Systems, 2017a). The primary advantage provided by the Spine Mentor is a more realistic simulation than cadavers. The Spine Mentor is suitable for practicing needle penetration for catheters, wires, and epidurals (Ponoroff, 2017). As an example of a cadaveric model, which in a 2014 study proved to increase mean self-reported confidence significantly, the Spine Mentor excels (Kirkman et al., 2014). The print design of the Spine Mentor is realistic to the touch. It has layers that simulate an actual spinal procedure, complete with low to no resistance pockets. The simulator includes a virtual C-arm that maneuvers during use (3D Systems, 2017b). The Spine Mentor is suitable for the following simulations: preoperative spine palpation, simulated fluoroscopic guidance, accessing the epidural space with loss of resistance technique, and percutaneous electrodes placement (3D Systems, 2017a).

2. Mouse Uterus

As recently as March 2016, scientists were limited in their ability to utilize 3D technology when studying the reproductive organs of mice for the purpose of eventual human application. The most common application was utilizing 3D scanning to determine how eggs attached to the uterus after fertilization (Burton, Wang, Behringer, & Larina, 2016). In 2017, researchers at Northwestern University in Chicago printed ovarian bio-prosthetics for mice. They removed ovaries from mice, and implanted artificial ovaries. The bio-prosthetics are a gelatin-based scaffold, which is a biological hydrogel constructed from broken down collagen, and is safe for use in humans. One of the most commonly referenced uses for this technology is the eventual replacement of ovaries in human women who have undergone cancer treatments. Of the seven mice that mated after treatment, three successfully gave birth (Sample, 2017). The experiment with the mice is much less complex than a human clinical trial would be. The scale is significantly smaller with mice and less complicated when it comes to achieving integration with blood vessels (Kornei, 2017).

3. Adidas Leverages CLIP

Adidas is currently realizing the future of 3D printing in mass production. Collaborating with Carbon 3D, Adidas has designed a 3D printed sole for its running shoes. The top of the shoe is constructed from conventional fabric and is attached to the sole after it is printed. This technology allows Adidas to change the physical characteristics of the sole, making parts stiffer for support, or more elastic for responsiveness as desired. The goal is that the user receives a customized athletically enhanced shoe. According to the *Wall Street Journal*, the costs associated with mass-producing the soles are lower than traditional manufacturing (Mims, 2017). However, this is only true when the quantity remains low. This is due to the high upfront costs of molding and setup commonly seen in traditional factories. According to the same article, three-dimensional printing retains the economic edge for any item that is making 20,000 parts or less, due to comparatively low set-up costs. Adidas plans to ship 5,000 pairs of the 3D printed shoes by the end of 2017, and 100,000 pairs by the end of 2018. By promoting the shoes via high-end marketing strategies and prices, Adidas effectively offsets any potential loss incurred by not utilizing traditional manufacturing (Mims, 2017).

This is not Adidas' first foray into the world of 3D printing. Adidas previously introduced the 3D Runners, which highlighted the available technology. However, with a $333 price tag and limited quantities, they proved more of a proof of concept than a realistic option for the standard consumer. The difference between the originals and the latest iteration lies in Adidas' partnership with Carbon 3D. By leveraging the increased print speeds of Carbon's CLIP technology, Adidas can produce enough shoes to make them a readily available asset capable of meeting market demand. Mass production of 3D printed shoes is only the first move in Adidas' marketing strategy, they eventually plan to provide customers the option of local customization to match their preferred style and individual needs (Tepper, 2017).

4. GE Propels 3D Printing Forward

GE is redesigning the possible by using additive manufacturing to support aerospace design. According to the *GE Report*, by designing a new engine called the Advanced Turbo Propeller (ATP), GE is manufacturing an engine that is over 35% printed. This new design combines the 885 parts of a standard propeller engine into a mere 12 parts. This redesign boasts a 10% increase in power, 20% increase in fuel efficiency, and a 5% overall weight reduction (Van Dussen, 2017). The report goes on to say that the reduction in moving parts results in another 1,000 hours of flight time before the required maintenance overhaul that is common in engines of the same class. These factors add up to a significant cost savings to the airlines, and by proxy to the consumer. Gordie Follin, the executive manager of GE Aviation's ATP program, summed up the importance of additive manufacturing to the company: "We're not putting so much effort into additive manufacturing because it's a sexy new technology for its own sake. It's demonstrably better. It lets us disrupt the process" (Van Dussen, 2017, p. 1). GE has already produced all of the parts, and is currently assembling the engine for critical testing. The first test flights begin in 2018, with commercial production following in 2020 (Van Dussen, 2017).

D. ADDITIVE MANUFACTURING WITHIN THE MARINE CORPS

The Marine Corps prides itself on being both expeditionary and innovative. One of the commonly used catch phrases is "improvise, adapt, and overcome." In 2014, the Marine Corps paid a consulting firm to produce an overview of additive manufacturing specifically tailored for the Marine Corps (Appleton, 2014). For the last several years, the Marine Corps and other components within the DOD, have been exploring additive manufacturing as a solution to common logistical problems. Examples of these problems include long lead times, OEM part unavailability, and emergency maintenance situations. These explorations have been largely limited to proof of concept and information gathering. Due to the emerging nature of this technology, there has not been a push for full-scale production of parts utilizing additive manufacturing.

1. Marine Administrative Message 489/16

The Marine Corps published Marine Administrative Message (Maradmin) 489/16 in an effort to harness the small unit leadership and innovation that has long been the trademark of Marine Corps success. The Maradmin serves as a general call to action for all Marines interested in the application of additive manufacturing. The general text outlines that all responses should avoid aviation-related items, and instead focus on ground solutions only. The required action section calls for all Marines to implement additive manufacturing processes and procedures in all ways related to the design and production of any part with M or X source codes. M-coded parts are generally consumables, while X-coded parts are obsolete (United States Marine Corps, 2016b). Per this Maradmin, production of parts with M or X source codes do not require legal review. This prevents Marines from dealing with the uncertainty and challenges associated with the use of Intellectual Property. Any deviation or design improvement on OEM specifications require routing to Marine Corps Systems Command (MCSC) in order to ensure safety (United States Marine Corps, 2016b).

2. Marine Corps Historical Perspective

The Marine Corps thrives on using speed as a weapon. Accomplishing this requires being lighter and more agile than their enemies, and translating that speed into the ability to protect surfaces and exploit enemy gaps (United States Marine Corps, 2001). Organizations like the Marine Expeditionary Unit (MEU) are self-sufficient for a short time. However, in places like Iraq and Afghanistan, as the duration of the mission increases so does the logistical footprint. This leads to a phenomenon referred to as the "Iron Mountain" or "Steel Mountain." The massing of equipment and repair parts near operations is prudent, and allows for effective logistical support. Shipping parts from the United States by air or sea is not effective due to the long lead times involved. This creates an artificial shortage in the supply chain. Places like Camp Leatherneck in Afghanistan and Al-Taqaddum Air Base (TQ) in Iraq are examples of Iron Mountains. For years, the DOD shipped assets to these locations, including both end items and repair parts. When the drawdown occurred, the Marine Corps and DOD faced the additional challenge of a logistical retrograde. Estimates place the gear requiring retrograde from Afghanistan to the United States at a value of $30 billion (AS Logistics, 2016). An entire command comprised of more than 60 military occupational specialties (MOSs) was setup to address this issue. The unit called Redeployment and Retrograde in support of Reset and Reconstitution Operations Group (R4OG) pulled Marines from across the Marine Corps to assist with the retrograde. Originally created in April 2012, R4OG received several awards for logistical excellence (Ostroska, 2014). While this unit was unequivocally effective, additive manufacturing may reduce similar future burdens placed on the Marine Corps. This will also partially eliminate the requirement to maintain redundant stock. Even a small percentage of parts being 3D printed would significantly reduce stocking requirements. Associated with those stocking requirements are the costs of procurement, initial transport, and retrograde. Additionally, these supply depots become ideal stationary targets for the enemy, and provide a critical vulnerability through general mishaps. An example of this is the fire at the Supply Management Unit (SMU) at Camp Leatherneck May 16, 2010. Conservative estimates place the total dollar value of assets lost in the millions (Ford, Housel, & Mun, 2017).

3. Marine Corps Installations and Logistics Command and Marine Corps Systems Command

Marine Corps Installations and Logistics Command (I&L) is continuously seeking improvements and efficiencies in the way it delivers logistical support to the warfighter. Next Generation Logistics is a subset of I&L that "advocates for the future of hybrid logistics, by exploring and exploiting emerging opportunities in order to rapidly transition logistics capabilities to the warfighter" (United States Marine Corps, 2017a, p. 1). Its core focus areas include the following:

a. *Unmanned Logistics Systems*

- Optionally manned legacy trucks and amphibious vehicles
- Squad autonomous cargo mules
- Large, medium, small cargo Vertical Take-off and Landing (VTOL) drones

b. *Smart Logistics*

- Ubiquitous sensors across equipment and Marines
- Mobile networks and personal devices
- Predictive data through big data and analytics

c. *Additive Manufacturing*

- Every Marine a maker
- In-field manufacturing of critical parts and customized unmanned systems, munitions, shelters
- Reduced obsolescence risks through rapid prototyping and production. (United States Marine Corps, 2017a, p. 1)

In the area of additive manufacturing, I&L oversees Marine Corps Systems Command (MCSC), who provide a myriad of programs related to additive manufacturing (C. Wood, personal communication, September 15, 2016). These efforts include Marine Maker Training, a weeklong course developing the skills necessary to apply practical additive manufacturing solutions in a tactical environment (United States Marine Corps, 2017d). Additional measures include the Expeditionary Manufacturing Trailer (EXMAN), a proof of concept additive manufacturing tool currently employed by 1st Maintenance Battalion, and the Expeditionary Fabrication Trailer (EXFAB), which stood up with 2nd Maintenance Battalion in July 2017 (G. Pace, personal communication, June 21, 2017). Both I&L and MCSC are seeking further saturation of additive manufacturing resources throughout the Marine Corps, and are receiving, vetting, and publishing the findings and solutions of the Marines at the tactical level (G. Pace, personal communication, June 21, 2017).

4. 1st Maintenance Battalion

1st Maintenance Battalion is the current home of the EXMAN trailer. The Marine Corps has tasked them with exploring additive manufacturing solutions (G. Pace, personal communication, June 21, 2017). Without a current order in place to specifically define Standard Operating Procedures (SOPs) and approved methods to accomplish the mission, the unit relies on innovative thinking and collaborative efforts to best utilize the assets on hand (G. Pace, personal communication, June 21, 2017).

a. Culture

Rather than focusing on metrics as a measure of success, the Commanding Officer has focused on fostering a culture of innovation and ownership within the command (G. Pace, personal communication, June 21, 2017). By creating an inclusive environment where all Marines are encouraged to participate, innovate, and allowed to fail, he effectively encourages the ingenuity of the Marines. Currently, approximately one dozen Marines are involved with the project on a strictly volunteer basis. The Commanding Officer's qualifications for participating in the EXMAN program are two-fold be motivated and be innovative (G. Pace, personal communication, June 21, 2017). This inclusive environment and all-volunteer team attracts Marines who are highly qualified. These Marines are capable enough within their own job to seek additional responsibilities and challenges (G. Pace, personal communication, June 21, 2017). Once a Marine is involved with the EXMAN project, he or she is encouraged to focus on the four buckets where additive manufacturing can have the most impact:

- Obsolete or unprocurable items that are no longer available through the standard supply system.
- Items with a long lead time for the necessary repair part.
- Timely restoration of critical assets by providing class IX (repair) parts.
- Echeloning of pieces to decentralize manufacturing. The goal is to leverage the knowledge and industry expertise, both material and intellectual, through the building of collaborative networks. (G. Pace, personal communication, June 21, 2017)

1st Maintenance Battalion achieves these goals while focusing on flexibility and adaptability. Knowing that the technology is increasing daily, the focus is to innovate with what is currently available rather than "chasing technology" (G. Pace, personal communication, June 21, 2017). The priority for the unit is flexibility over technology. 1st Maintenance Battalion demonstrates the mindset by rotating ownership between companies within the battalion. All Marines are welcomed and encouraged to participate, but the physical ownership and upkeep responsibilities rotate throughout the battalion. The intent of this access is to foster ownership and increase the individual Marine's commitment to the overall mission (G. Pace, personal communication, June 21, 2017).

b. Tactics Techniques Procedures and Equipment

A staff sergeant with direct oversight from a gunnery sergeant and a chief warrant officer currently manage the EXMAN Trailer daily. When the EXMAN Trailer rotates to another company, different personnel will assume leadership positions. The battalion is working to develop standard operating procedures (W. Jones, personal communication, June 21, 2017). They have wide latitude in terms of creativity and the ability to experiment (G. Pace, personal communication, June 21, 2017).

1st Maintenance Battalion has received some constraints from Headquarters Marine Corps (HQMC). The intent of these constraints is to maximize safety and promote the promulgation of data. The Marine Corps requires the battalion to print in primary colors for safety purposes. This differentiates the printed items from OEM parts (G. Pace, personal communication, June 21, 2017). 1st Maintenance Battalion submits stereolithography (STL) files, along with a short write-up, to HQMC for approval. This allows HQMC to maintain visibility on all printed data. 1st Maintenance Battalion routes packages to MCSC, who then route to I&L, where vetting for suitability (fit, form, and function) and Intellectual Property (IP) is accomplished. HQMC also catalogues these submissions for future dissemination throughout the Marine Corps (D. Bower, personal communication, June 21, 2017). At the unit level, 1st Maintenance Battalion Commander primarily focuses on providing material solutions to maintenance issues (G. Pace, personal communication, June 21, 2017). Additionally, the Commandant of the Marine

Corps directly charged the unit with innovation and testing the capability and limits of their current equipment (G. Pace, personal communication, June 21, 2017).

Within 1st Maintenance Battalion, the Commanding Officer has established his own internal controls. He retains the authority to authorize the use of any manufactured maintenance solution for equipment that is organic to the Battalion and briefed to him in advance (G. Pace, personal communication, June 21, 2017). 1st Maintenance Battalion leverages additive manufacturing for creative solutions in its upkeep of equipment owned by supported units. For these units, the authorization to utilize manufactured parts resides with the commander who owns the equipment (G. Pace, personal communication, June 21, 2017).

1st Maintenance Battalion is equipped to scan, print, and convert files for use on a CNC machine. This process starts with scanning, which is currently conducted utilizing a Creaform Go Scan 3D, a fourteen-month-old light scanner, initially purchased for $25,000 (T. Arndt, personal communication, June 21, 2017). There are distinct capability differences between light and laser scanners. The current scanner does not have the same intuitive features that newer models have, and is less effective with detailed items. The staff requires between one and two days to train a Marine to use the scanner (T. Arndt, personal communication, June 21, 2017). The Marines generally prefer to design STL files from scratch using Solidworks design software (W. Jones, personal communication, June 21, 2017).

While not directly related to the 3D printing, the Marines utilize a TORMACH Personal CNC 1100 to achieve finishing (machining and milling). This runs on 208 volts and provides a small work area (T. Arndt, personal communication, June 21, 2017). 1st Maintenance Battalion Marines design their projects with either computer aided design (CAD) or computer aided manufacturing (CAM). The Marines then convert to drawing interchange format (DXF) or drawing (DWG), and then transfer the files to the machining trailer for milling. Once the Marines validate the fit, form, and function in plastic, they machine the item and test for quality assurance (W. Jones, personal communication, June 21, 2017).

1st Maintenance Battalion accomplishes 3D printing utilizing a Fortus 250MC printer manufactured by Stratasys. This printer has a single print head, two cartridge slots (one for build material and one for support material), and runs on 120 volts. Dual tone printing is possible if the item does not require support material (W. Jones, personal communication, June 21, 2017). The printer utilizes a filament that comes pre-spooled from Stratasys, and includes proprietary data chips that monitor the remaining filament levels (W. Jones, personal communication, June 21, 2017). These spools are available at a cost of $235 each. The raw material is available for manual spooling at a cost of $30 (T. Arndt, personal communication, June 21, 2017).

All of these materials are stored and operated in a container previously utilized as a radar monitoring station. The integrated wiring for power and sealed openings provide an inherent system integrity during adverse weather conditions (T. Arndt, personal communication, June 21, 2017). The exterior dimensions are equal to that of an international organization for standardization (ISO) container (20’x8’x8’). This means that if the required environmental control unit (ECU) is loaded inside the container, the entire package can be loaded on a logistics vehicle system replacement (LVSR) and transported with equipment that is organic to the unit. With these assets, the battalion can take an operational EXMAN Trailer and prepare it for movement within one hour. Upon arriving at a destination, it can be operational within one hour if using generator power. If using a land-based power grid, two hours are required to be operational (W. Jones, personal communication, June 21, 2017).

c. Challenges

Attempts to innovate and change established practices are challenging in a variety of ways. Adherence to doctrine, while prudent, slows the process for the end user and limits the speed of change. The parts approval process is one example of this challenge. The initial paperwork requirements are minimal, however, the time required to achieve organizational level approval is significant (G. Pace, personal communication, June 21, 2017).

Legal and IP challenges are present at the I&L level. These challenges do not affect the current practice of providing proof of concept and one-off maintenance solutions (G. Pace, personal communication, June 21, 2017). However, future attempts to push this technology across the force will be subject to these constraints. The concern is that the complexity of the problem leads to a risk adverse environment where the status quo is inaction (G. Pace, personal communication, June 21, 2017).

1st Maintenance Battalion initiated market research with Carbon 3D, in an attempt to harness their CLIP printing technology (D. Bower, personal communication, June 21, 2017). There were several distinct challenges with this collaboration. Carbon 3D was initially believed to require a constant network connection with their printers. This would be problematic for the Marine Corps, where the machine must be deployable and mobile. However, Carbon 3D only requires a network connection to initiate a print order. The next difficulty lies in the liquid resin required for vat photopolymerization printing, which has a short life span after introduction to the printer and is comparatively expensive. This presents an additional logistical challenge in keeping the resin stocked in an austere environment. The machine also has strict leveling requirements, which a constant network connection alleviates by assisting with remote leveling. Without this connection in an austere location, the functionality of the machine may be impaired. The final challenge is the lease only option currently marketed by Carbon 3D. The Marine Corps will pay a premium to use the asset and not retain ownership at the end of the lease. Units could distribute a purchased machine to another unit to continue to foster innovative behavior (D. Bower, personal communication, June 21, 2017).

Additional communication with Carbon 3D addresses the aforementioned concerns: the network connection is necessary to initiate a print, but not for completion. The liquid resin lifespan is reasonable as long as it is stored in its original container. Resin requires immediate use once added to the printer. Finally, the lease-only option remains Carbon 3D’s business model, but with a sufficient order (50 or more printers) they are willing to customize the hardware to the Marine Corps’ specifications (P. DeSimone, personal communication, September 14, 2017)

d. Successes and Innovations

Given the permissive command environment and approval to experiment, the Marines of 1st Maintenance Battalion have achieved some noteworthy successes in the areas of new capabilities, proof of concept items, and collaboration. Innovative thinking combined with leveraging 3D printing led to the generation of 3D representations of training environments. Figure 10 is an example of this innovation.

Figure 10. 3D Terrain Model

These 3D maps are handheld graphical representations, and are available to 1st Intelligence Battalion (T. Arndt, personal communication, June 21, 2017). This represents a previously undeveloped capability with unknown battlefield applications. Intelligence Marines have the capability to combine near real-time data with 3D printing to provide scaled terrain models depicting current conditions on a dynamic battlefield. The capability for the Marine Corps to access 3D graphical representations of an area was previously only available through contracting and third-party vendors (W. Jones, personal communication, June 21, 2017).

Proof of concept items have been the hallmark of this program. Marines pursue items that are either consistently ordered, or maintain long lead times (G. Pace, personal communication, June 21, 2017). Examples of these include the impeller fan for the

Abrams tank, power knob for optics (AN/PVS-17c), night vision goggle helmet mounts, and camera mounts for Explosive Ordinance Disposal (EOD) robots (MK-2) (W. Jones, personal communication, June 21, 2017).

A corporal initially developed the impeller fan design. This Marine pursued the idea over a weekend without any government assets or support. The idea was then refined by the section Staff Non-Commissioned Officer (SNCO), and sent to Space and Naval Warfare Systems Command (SPAWAR). SPAWAR then prototyped a fan and utilized a Cooperative Research and Development Agreement (CRADA) with Methods 3D to print a metal version of the fan. SPAWAR then tested functionality with an artificial power supply resulting in a performance within standards (G. Pace, personal communication, June 21, 2017).

The power knob for the AN/PVS-17c is a frequently damaged part. Replacements were not available individually, but rather came as part of an assembly set costing more than $4,000. Through the efforts of 1st Maintenance Battalion, the part requires 14 minutes to print (W. Jones, personal communication, June 21, 2017). Design for the AN/PVS-14 night vision goggle mounts requires four hours. The Marines are capable of printing them in five hours, and installing them in five minutes (W. Jones, personal communication, June 21, 2017).

The MK-2 EOD robot utilizes a circular plastic camera mount. The forces involved in training cause this item to experience a high failure rate. Through innovative design improvements, the Marines of 1st Maintenance Battalion were able to strengthen the structural design and print an improved version in five hours (W. Jones, personal communication, June 21, 2017).

1st Maintenance Battalion utilizes the Solidworks design program to create the items they eventually print. Solidworks utilizes STL files, which is the industry standard for 3D printing. The battalion also possesses a shop equipment machine shop (SEMS), which is a major end item consisting of a lathe and a mill. HQMC assigned the SEMS a Table of Authorized Material Control Number (TAMCN) of C79127B. This is an organic asset to all Maintenance Battalions (T. Arndt, personal communication, June 21, 2017).

The SEMS utilizes DXF and DWG files, derived from the original STL files in solid works. This allows the Marines to print in plastic and check fit, form, and function before machining a metal part. This is not a replacement for printing in metal, however it provides an important capability to the unit for both proof of concept and emergency maintenance (W. Jones, personal communication, June 23, 2017).

With the focus on developing and adapting the emerging technologies of additive manufacturing, collaboration is a key component of the strategy for the Marine Corps (G. Pace, personal communication, June 21, 2017). I&L, via the Next Level Logistics branch, oversees the additive manufacturing programs of MCSC. MCSC serves as the direct higher command (for the purposes of additive manufacturing) to 1st Maintenance Battalion, and processes all requests for approval and documented successes achieved (G. Pace, personal communication, June 21, 2017). SPAWAR is supporting the Naval Additive Manufacturing Implementation Plan, which serves as the overarching program that contains all USMC additive manufacturing. As such, SPAWAR serves as the contracting vehicle for asset purchases, and was instrumental in establishing the first CRADA with Methods 3D (K. Holzworth, personal communication, June 23, 2017). SPAWAR initially designed this CRADA to enable the production of a power shift yoke. This asset was the first fully approved additive manufacturing item to originate from this line of effort (D. Bower, personal communication, June 21, 2017). SPAWAR is currently attempting to widen the scope of the CRADA with Methods 3D in order to allow production of the impeller fan in addition to the originally approved production of the power shift yoke (K. Holzworth, personal communication, June 23, 2017). MCSC is attempting a second collaborative effort in the form of a bailment with General Electric (GE) Additive (K. Holzworth, personal communication, June 23, 2017). The negotiations for this are ongoing, and successful implementation will add additional resources and capabilities to the Marine Corps' expanding additive manufacturing efforts.

e. Way Forward

The Marine Corps has experienced significant growth in additive manufacturing over the last two years (G. Pace, personal communication, June 21, 2017). This growth has led to a refinement in requirements, capabilities, and a series of potential end-states. 1st Maintenance Battalion has taken a strong stance against “chasing technology;” however, they are looking to upgrade to proven commercial off the shelf (COTS) assets every 18-24 months (G. Pace, personal communication, June 21, 2017). This will allow them to mirror the civilian market capabilities without accepting unnecessary risk associated with unproven technologies. 1st Maintenance Battalion is currently attempting to upgrade from a Fortus 250 to a Fortus 450 printing platform (T. Arndt, personal communication, June 21, 2017). The Marine Corps will retain ownership of the Fortus 250, as an additional capability for the EXMAN Trailer, which will be a significant benefit in the future. The Fortus 450 is capable of printing in three materials ABS, ultem, and nylon (W. Jones, personal communication, June 21, 2017). This represents a realized improvement from the Fortus 250, which only prints in ABS. The battalion is also exploring upgrading their current light scanner to a laser scanner. There is no current model or price range established for this upgrade (W. Jones, personal communication, June 21, 2017).

The stated objective of 1st Maintenance Battalion is to explore the capabilities and limitations of the technology offered in order to provide solutions and innovations for the Marine Corps (G. Pace, personal communication, June 21, 2017). Battalions do not have authorization to dictate future structure across the Marine Corps. However, as the test-bed for the emerging technology, 1st Maintenance Battalion is poised to present a viable plan for the future expansion of this capability. They base their proposed vision for the future on echeloning printers in nodes by capability, utilizing the same structure as maintenance equipment (G. Pace, personal communication, June 21, 2017). At the organizational level, units like Infantry Battalions and Combat Logistics Battalions may only possess a desktop 3D printer. This would afford the capability of printing ABS remotely without assistance from higher commands. At the intermediate level, units such as 1st Maintenance Battalion would be equipped with assets like the SEMS, multi-material printers, and scanners. Other units would maintain larger and less mobile printers at the depot level. These assets enable printing in metal along with a wider range of capabilities (G. Pace, personal communication, June 21, 2017). This fielding plan aligns with the system already in place for general maintenance, allowing lower level units to achieve realistic results before escalating to a unit with more capabilities. Additionally, this lessens the total requirement for assets, and provides more flexibility. The actual assets assigned at each level are placeholders. Private industry has recently scaled down metal 3D printers to desktop size (Desktop Metal, 2017). These assets may be more feasible in the future. A mobile battalion engaged in combat, or supporting combat operations, requires different capabilities than an intermediate support command (G. Pace, personal communication, June 21, 2017). The basis for the future model of information management may resemble an iTunes style file-sharing program (G. Pace, personal communication, June 21, 2017). In this scenario, maintainers at the lowest level can experience equipment failure, download an STL file, and print the required part. If they lack the printing capability, they escalate to the next maintenance level. The least preferred method of accomplishing this is an additional Marine Corps contract utilizing a third-party vendor to design software. The most preferred method would be a hybrid expansion of the existing Federal Logistics Data (FEDLOG) or Web Federal Logistics Information Service (WEBFLIS) system. This requires the establishment of a separate category within the program used to store approved data files (G. Pace, personal communication, June 21, 2017). SPAWAR is actively looking to create a blockchain system for all fully approved files (K. Holzworth, personal communication, June 23, 2017). A blockchain system will prevent editing or manipulation of data files after the vetting and approval process (K. Holzworth, personal communication, June 23, 2017). In pursuit of this goal, SPAWAR is forming alliances with IBM and Intel to leverage industry capabilities (K. Holzworth, personal communication, June 23, 2017).

III. LITERATURE REVIEW

A. INTRODUCTION

This chapter is divided into three sections, each covering a portion of the literature available on additive manufacturing in specific areas. The chapter begins with the widest scope, the state of the additive manufacturing industry. It then narrows to the state of additive manufacturing within the DOD. The final and narrowest focus is the state of additive manufacturing within the Marine Corps.

This literature review includes applicable theses, studies, journal entries, newspaper articles, online articles, and industry reports. There is an abundance of resources regarding the state of the industry. However, the published research available diminishes as the topic narrows to the DOD, and again to the Marine Corps.

B. STATE OF THE INDUSTRY

There is enthusiasm surrounding the expanding field of additive manufacturing. As a result, there are adequate resources available regarding the state of the industry. This includes publications such as the *Wohlers Report*, professional articles, and published theses. The consensus is that the industry is still in the early stages of growth and exploring technological limits (Wohlers et al., 2017). This section expands on the data available within the *Wohlers Report*, reports on the exploration of current technologies, and briefly discusses intellectual property particularly as it relates to government contracts.

1. Wohlers Report

The *Wohlers Report* is an "annual worldwide progress report, regarding 3D printing and additive manufacturing State of the Industry" (Wohlers et al., 2017, p. 15). Based on their evaluation, additive manufacturing currently accounts for 0.047% of total manufacturing worldwide. This equates to $6.1 billion as of 2016 (Wohlers et al., 2017). The industry tipping point occurred in the third quarter of 2012, as corporations and private consumers embraced new technological advances. The result was an increase of more than $1 billion annually in total worldwide manufacturing for the period of 2012 to 2016. Their market analysis forecasts predict additive manufacturing will rise to 5% of total manufacturing worldwide resulting in a $640 billion industry (Wohlers et al., 2017). The *Wohlers Report* for 2017 conducted brief analyses of 76 companies (Wohlers et al., 2017). Many of these companies have distinguished themselves as frontrunners within the 3D printing industry. The following four are representative of these leaders this is not an exhaustive list, and is in alphabetical order, not based on any qualitative assessment. The one notable company not covered by the *Wohlers Report* is NewPro 3D, a Canadian company which in many ways parallels Carbon 3D.

a. 3D Systems

3D Systems is an American company based out of Rockhill, NC. It became the first company to commercialize additive manufacturing when it sold a stereolithographic system in 1988 (Wohlers et al., 2017). In addition to their historical success, 3D Systems is continuing to expand, purchasing three companies between 2014 and 2017 (Wohlers et al., 2017). This expansion is primarily in pursuit of capabilities within the dental field. The company currently has regulatory approval to use 3D printing for dental purposes in 70 countries (Wohlers et al., 2017). In 2016, 3D Systems opened a 70,000-square-foot healthcare technological center in Littleton, CO, where they continue to advance their surgical simulation software. Within this facility, they have dedicated specific areas for anatomical models, prosthetics, metal devices, and orthopedic implants.

b. Carbon 3D

Carbon 3D is a private (not publicly traded) American company based out of Redwood City, CA. They introduced “a new photopolymer technology called CLIP in March 2015” (Wohlers et al., 2017, p. 72). Joseph DeSimone is the president and CEO of Carbon 3D (Securities and Exchange Commission [SEC], 2016). In March 2015, he discussed CLIP at a TED Talk, where he introduced an intricate geodesic sphere, not reproducible with standard subtractive manufacturing (DeSimone, 2016). This demonstration was effective marketing, and to date, the video has more than 2.4 million online views. The board of directors for Carbon 3D includes Alan Mulally, who gained notoriety with both Ford and Boeing (SEC, 2016). Carbon 3D's marketing and personnel selection has led to success within their industry. They have partnerships with Kodak, Johnson & Johnson, GE Ventures, Nikon, and BMW. Carbon 3D is well financed, receiving more than $220 million from investors such as Autodesk's Spark Investment Fund and Google Venture (Wohlers et al., 2017). The company sold their first system in 2016 and introduced epoxy resins this year (Wohlers et al., 2017).

c. GE Additive

GE Additive is a business unit of General Electric (GE), an American company based out of Boston, MA. In 2016, the annual CEO letter notified shareholders that additive manufacturing was "a transformative technology" (Wohlers et al., 2017, p. 83), and would be a focus moving forward. Jeffery Immelt, the CEO, stated that the new intent was to be "both a consumer of the technology, and in the business of additive" (Wohlers et al., 2017, p. 83). In order to facilitate this entry into the additive manufacturing market, GE acquired controlling interest in two European companies in late 2016. In October, GE acquired the German Concept Laser GmbH, and in December, GE acquired the Swedish Arcam AB (Wohlers et al., 2017). The *Wohlers Report* characterizes these acquisitions as "two of the largest and most significant deals in the additive manufacturing industry" (Wohlers et al., 2017, p. 83). David Joyce, the CEO of GE Aviation, currently manages GE Additive. The company has stated that they intend to "sell about 10,000 machines over the next decade, with 10% going to GE" (General Electric, 2016).

d. Stratasys

Stratasys is an Israeli owned company with dual headquarters in Rehovot, Israel, and Eden Prairie, MN (Wohlers et al., 2017). The dual headquarters are the result of a merger between Stratasys and Objet in 2012 (Wohlers et al., 2017). In 1991 Stratasys sold its first material Extrusion system (which they market as fused deposition modeling); and to date has sold more industrial machines than any other manufacturer (Wohlers et al., 2017). Objet was responsible for the development of PolyJet, which uses inkjet printing technology and photopolymers to achieve a material jetting process (Wohlers et al., 2017). Additionally, in 2013 Stratasys purchased Makerbot Industries, commonly known for their desktop printer series (Wohlers et al., 2017). In 2016, Stratasys reported more than $670 million in revenue and invested in Desktop Metal, an American startup working to miniaturize metal printing (Wohlers et al., 2017).

2. Current Technologies

With the growth of additive manufacturing over the last 10 years, there has also been incredible technological growth within the industry. This section reviews advances in four of those areas without a specific order. Those advances are medical technology, manufacturing or commercialization, home-use, and metal printing. Each of these areas have experienced tremendous growth, and this section introduces the reader to current advances and possibilities.

a. Medical Advances in Literature

There are many legitimate sources detailing the benefits 3D printing brings to both current and future medicine. The “Background” chapter (Current Events) discussed the printing of uteruses in mice leading to successful live births (Sample, 2017). This method of printing uses biological material as a scaffold. There are many other similar advances centered on printing biological material. The University of Melbourne (Australia) published an article detailing advances to medicine and specifically addressed tissue engineering and bio-printing (Trounson, 2017). Currently, scientists are bio-printing “organoids,” which mimic organs on a smaller scale and are used for research (Trounson, 2017). However, there are significant limitations with the current technology that prevent scaling them to full size. The cells die within several minutes of introduction into the gel if not “transferred back into a nutrient solution” (Trounson, 2017). This is not a problem when printing organoids; however, scaling the size up requires longer printing times, and therefore is not currently sustainable.

In May 2015, SmarTech released a report capturing the current state and forecasted state of 3D printing within the dental industry (Tampi, 2015). According to the report, “dentistry has begun to not just explore but actually realize the comparative advantage of using 3D scanning, modeling, and printing tools” (Tampi, 2015). In 2014, 3D printed dental machines and products accounted for more than $780 million in revenue. The SmarTech report projects revenues in excess of $3 billion by 2020 for the dental industry.

b. Manufacturing and Commercialization Literature

The “Background” chapter introduced the commercialization of 3D printing, regarding the partnership between Carbon 3D and Adidas. This partnership is mutually beneficial and provides Adidas with the ability to print more customized athletically enhanced shoes (Tepper, 2017). This is not a unique partnership. *The Economist* published an article in June 2017 that outlines several manufacturing partnerships (“3D Printers Start to Build,” 2017). The article references Carbon 3D’s relationship with not only Adidas, but also with Caterpillar and John Deere. These companies are “working with Carbon on moving their warehouses, in effect, to the online cloud, whence digital designs can be downloaded to different locations for parts to be printed to order” (Economist, 2017). Carbon 3D is not the only company collaborating with industry for manufacturing. Stratasys teamed up with both Boeing and Ford in 2016 to optimize manufacturing applications on a large scale (Heater, 2016).

Commercialization also occurs in other areas of industry. *The Washington Post* reported on a company named Apis Cor, which 3D prints houses (Marks, 2017). The material used to print the house is concrete and finishing work is required (Marks, 2017). However, Apis Cor completed the proof of concept in less than a day at a cost of less than $10,000 (Marks, 2017). The printer resembles a tower crane, and is centrally located with a revolving reach that adds material along the *X*-axis, *Y*-axis, and *Z*-axis (Apis Cor, 2017).

c. Literature Concerning Home Use

Home use in the 3D printing world in synonymous with the Maker Movement. According to the University of California at Davis, the Maker Movement is “a community of hobbyists, tinkerers, engineers, hackers, and artists who creatively design and build projects for both playful and useful ends” (Martin, 2015, p.1). In pursuit of these hobbies, makers utilize low-cost 3D printers (desktop printers) that are especially suited for home use. The *Wohlers Report* defines desktop 3D printers as "AM systems that sell for less than $5,000. The category includes RepRap derivatives and products from XYZprinting, Tiertime, Ultimaker, MakerBot, Rokit, Printrbot, Aleph Objects, and many others" (Wohlers et al., 2017, p. 157). California Congressman Mark Takano is an advocate of the Maker Movement. In March of 2016, he published an article advocating community leaders to transition closed Walmarts and similar box stores to Makerspaces (Takano, 2016). An *Atlantic* article on the Maker Movement claims it is a gateway to reinvigorating the U.S. economy. The article cites several examples of small maker spaces and the impact they have had on the local community (Fallows, 2016).

d. Metal Printing Literature

3D metal printing is still an immature technology. However, the maturation of the technology is evident within industry today. According to Anatol Locker (2017) from All About 3D Printing, the applications for semi-metal home printing are in place, while full metal printing is now available to the average Maker through online services. The home applications consist of metal powder infused filaments that make printing possible at the lower temperatures standard to home 3D printers (Locker, 2017).

As metal 3D printing technology expands, scientists are exploring new applications. Engineers at Northwestern recently published their advances in 3D metal printing (Morris, 2016). They eschewed the traditional powder and laser approach in favor of liquid printing. According to Amanda Morris' Northwestern University article, "despite starting with a liquid ink, the extruded material instantaneously solidifies and fuses with previously extruded material, enabling very large objects to be quickly created and immediately handled" (Morris, 2016). The engineers "uncoupled the printing and sintering" processes, making the process less difficult holistically. However, the printed objects require a heating process after printing in order to complete the production.

3. Governmental Guidance on Intellectual Property

One of the most cited challenges associated with 3D printing is the legal implications of reproducing designs that belong to someone else. According to the World Intellectual Property Organization (WIPO):

> Protecting an object from being printed in 3D without authorization does not raise any specific IP issues as such. Copyright will protect the originality of the work and the creator's right to reproduce it. This means that if copies of an original object are 3D printed without authorization, the creator can obtain relief under copyright law. Similarly, industrial design rights protect an object's ornamental and aesthetic appearance—its shape and form—while a patent protects its technical function and a three-dimensional trademark allows creators to distinguish their products from those of their competitors (and allows consumers to identify its source). (Malaty & Rostama, 2017, p. 1)

These basic definitions and concepts are critical to understanding the situation and requirements with which government organizations must contend. There are a number of governmental resources available that provide guidance in these areas. These resources include but are not limited to the Federal Acquisition Regulations (FAR), Defense Federal Acquisition Regulations Supplement (DFARS), and *Intellectual Property: Navigating through Commercial Waters*.

a. Federal Acquisition Regulations

The FAR provides broad guidance for government acquisitions. There are two parts in the FAR that provide guidance related to intellectual property. Part 27 focuses on definitions and direction (FAR 27), while Part 52 contains clauses related to intellectual property (FAR 52).

Part 27 of the FAR states that it is applicable to all agencies. Those agencies are free to deviate from the FAR in order to "meet the specific requirements of laws, executive orders, treaties, or international agreements" (FAR 27.101). The FAR goes on to state that "the Government recognizes rights in data developed at private expense, and limits its demands for delivery of that data. When such data is delivered, the Government will acquire only those rights essential to its needs" (FAR 27.102). The implications for printing repair parts are very clear. The government, being respectful of data rights, will need to arrange payment or permission in advance if printing parts intellectually owned by an outside entity.

Part 52 in the FAR contains provisions and clauses. FAR 52.227 contains 23 provisions and clauses directly related to intellectual property. These clauses and provisions are included in government contracts and generally protect the government's interests. One example of this is FAR Part 52.227-3 "Patent Indemnity." This clause indemnifies the government from infringement and costs "arising out of the manufacture or delivery of supplies, the performance of services, or the construction, alteration, modification, or repair of real property" (FAR 52.227-3). This clause does not protect the government from legal action stemming from the internal production of intellectually owned 3D printed parts. However, if included in a contract with an outside entity, it shifts liability to the outside entity, and provides indemnification for the government.

b. Defense Federal Acquisition Regulations Supplement

The FAR provides broad guidance to the government while the DFARS provides specific guidance to the DOD. The DOD modified the DFARS, which changed section 227. Previously the DFARS reserved sections 227.7001 to 227.7039 for clauses related to intellectual property (USD [AT&L], 2001). The DFARS now provides more detailed groupings when listing clauses related to intellectual property (DFARS 227). The following subparts are laid out for DOD employees, each with specific clauses relating to the topic:

- Subpart 227.70—Infringement Claims, Licenses, and Assignments
    - Five required clauses.
    - Three clauses used when applicable.
    - Seven additional clauses.
- Subpart 227.71—Rights in Technical Data
    - Implements requirements from nine Executive Orders or laws.
    - Defines unlimited rights, government purpose rights, and limited rights.
- Subpart 227.72—Rights in Computer Software and Computer Software Documentation
    - Implements requirements from six Executive Orders or laws.
    - Does not apply to software acquired from GSA schedule contracts.
    - Does not apply to release of software to litigation support contractors.

c. Intellectual Property: Navigating through Commercial Waters

In 2001, the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]) published *Intellectual Property: Navigating through Commercial Waters*. This publication is a response to the USD (AT&L)'s directive to "shift in focus for negotiating IP contract terms with commercial firms that ordinarily do not do business with the DOD" (USD[AT&L], 2001, p. iv). The stated intent of the publications is to "provide a straightforward discussion of information contracting officers need to negotiate IP arrangements" (USD[AT&L], 2001, p. iv). This reference is not all inclusive and is not meant to fully explain every detail of IP (USD[AT&L], 2001). However, this guide does provide a number of valuable resources for the layperson handling IP issues from the government's standing. Additionally, the solutions given in the resource are applicable to CRADAs given "appropriate legal counsel" (USD[AT&L], 2001, p. v).

In the first chapter, USD (AT&L) proposed five core principles for the DOD Acquisition Community:

- Integrate IP considerations fully into acquisition strategies for advances in technologies in order to protect core DOD interests.
- Respect and protect privately developed IP because it is a valuable for of intangible property that is critical to the financial strength of a business.
- Resolve issues prior to award by clearly identifying and distinguishing the IP deliverables from the license rights in those deliverables.
- Negotiate specialized IP provisions when the customary deliverables or standard license rights do not adequately balance the interests of the contractor and the government.
- Seek flexible and creative solutions to IP issues, focusing on acquiring only those deliverables and license rights necessary to accomplish the acquisition strategy. (USD[AT&L], 2001, p. 1–1)

In the second chapter USD (AT&L) draws a clear distinction between two categories of IP law. The first category consists of "patents, copy rights, trade secrets, trademarks, and service marks" (USD[AT&L], 2001, p. 2–1). The second category is "less common" and composed of vessel hull designs and mask works (USD[AT&L],

2001, p. 2–1). USD (AT&L) provided a table listing the common types of IP and their associated protection (shown in Table 1).

Table 1. The Most Common Types of Intellectual Property Protections. Adapted from USD(AT&L) (2001).

Type of IP Protection	Protectable Subject Matter	Nature of Protection/Rights Granted to the IP Owner	Requirements for Protection	Remedies Available	Duration of Protection	Statutory Basis	DoD-Specific Statutes/Regs
Patents	Processes, ma-chines, articles of manufacture, and compositions of matter.	Right to exclude others from making, using, selling, or importing the invention; sometimes referred to as the right to exclude others from "practicing" the invention.	Application filed in U.S. Patent & Trademark Office; invention must be new, useful, and non-obvious.	Money damages and injunction.	20 years from appli-cation date.	Title 35 U.S.C.; 28 U.S.C. 1498(a).	FAR 27.1 to 27.3 and related clauses; DFARS 227.3 and 227.70, and related clauses.
Copyrights	Original, creative works fixed in a tangible medium of expression (e.g., literary, musical, or audiovisual works; computer programs).	Exclusive right to (1) copy; (2) modify; (3) perform; (4) display; and (5) distribute copies of the copyrighted work. No protection against independent creation of similar works, or against certain "fair uses."	Automatic when fixed in a tangible medium; added remedies for registration and notice.	Money damages (actual or statutory), injunction, and criminal sanctions.	Life of the author plus 70 years.	Title 17 U.S.C.; 28 U.S.C. 1498(b).	10 U.S.C. 2320 and 2321; DFARS Subparts 227.71 and 227.72, and related clauses.
Trade Secrets	Any information having commercial value by being kept secret (e.g., technical, business, or financial information)	Right to control the disclosure and use of the information through contracts or nondisclosure agreements; protection against theft or misappropriation of that information, but not from independent creation or discovery by another party.	Must take reasonable steps to safeguard the information from disclosure; reasonableness depends on the value of the information.	Money damages, injunction, and criminal sanctions.	Potentially unlimited, as long as remains secret	18 U.S.C. 1905; 18 U.S.C. 1831-39; various state laws.	10 U.S.C. 2320 and 2321; DFARS Subparts 227.71 and 227.72, and related clauses.
Trademarks and Service Marks	Distinctive words, phrases, or symbols that identify the source of goods or services.	Protection from confusingly similar marks, deception, and unfair competition in the marketing of goods and services.	Automatic upon use in commerce; added remedies for registration and notice.	Money damages, injunction, and criminal sanctions.	Federal registration can be renewed every 10 years.	Title 15 U.S.C.; various state laws.	None; although a new draft FAR subpart is under development.

The third chapter focuses on acquisition of IP and "identifying the critical issues prior to contract award" (USD[AT&L], 2001, p. 3–5). The final chapter addresses common issues and provides solutions. The format is reminiscent of a frequently asked questions section (USD[AT&L], 2001).

C. STATE OF ADDITIVE MANUFACTURING IN THE DOD

Compared to industry literature, there are fewer sources related to DOD-specific additive manufacturing. This is a logical result of the narrowing of the scope from the entirety of the industry to just the DOD. Available sources include Government Accountability Officer (GAO) reports, official memorandums, academic theses, and an assortment of third party articles. The majority of available information can be categorically divided into three main topics: the DOD additive manufacturing call to action, DOD specific technologies, and challenges associated with the DOD.

1. DOD Additive Manufacturing Call to Action

GAO reports and DOD directives provide the most legitimate source material. The DOD has shown a collective desire to embrace the emerging technologies of additive manufacturing in order to increase military capabilities. In 2014, the DOD briefed the Senate Armed Services Committee (SASC) on additive manufacturing. The focus centered on three critical areas: "potential benefits and constraints, potential contributions to DOD mission, and transition of the technologies of the National Additive Manufacturing Innovation Institute for DOD use" (GAO, 2015, p. 2). As part of this report, the Senate ordered the GAO to conduct an analysis of the DOD's report (GAO, 2015). The GAO's findings in article GAO-16-56 indicated that the DOD had successfully met the intent of the Senate. GAO further recommended that the DOD design and implement a method of tracking additive manufacturing activities across the department.

In 2015, as Secretary of the Navy, Ray Mabus issued a memorandum calling for the fleet to capitalize on the potential of additive manufacturing. The memorandum stated, "Around the fleet, our Sailors and Marines are embracing AM" (Office of the Chief of Naval Operations (CNO), 2015, p.1). Additionally, this directive tasks the Assistant Secretary of the Navy (Research, Development and Acquisition) with establishing "an integrated and detailed implementation plan" (Office of the Chief of Naval Operations (CNO), 2015, p.1). Since the release of this call to action, the fleet has embraced additive manufacturing; resulting in the successful flight of a Marine Variant of the Osprey aircraft featuring 3D printed parts (Newman, 2017). Likewise, the Navy, through a partnership with Oak Ridge National Laboratory, TN created the first 3D printed submersible hull (Jackson, 2017).

The Navy is seeking to continue implementation of innovative solutions while respecting intellectual property. The proposed method to achieve this involves block and chain, an encrypted data system that guarantees file integrity (Schneider, 2017). This would allow the Navy to access the files for required parts, while simultaneously ensuring the correct file is used, and reimburse the company who owns the file (Schneider, 2017).

2. DOD-Specific Technology

The technological advances within additive manufacturing, specific to the DOD are largely reported in an online format, and are unique when compared to industry. This is readily apparent in the development and fielding of the Aerojet Rocketdyne AR1 rocket booster engine (Aerojet Rocketdyne, 2015). The initial design began in 2014. Success in the early stages led to the 2015 Defense Authorization Act mandating this engine as a substitute to the Russian provided RD-180 (Aerojet Rocketdyne, 2015). The AR1 is on track for a 2019 fielding, which will supply American made equipment, thus increasing national security (Aerojet Rocketdyne, 2015).

Another example of DOD specific technology is the U.S. Army collaboration with Rapid Equipping Forces, used to create and manage expeditionary laboratories (Millsaps, 2017). As a demonstration of their ability to create original solutions, the Army displayed the life of a breaching tool from design to implementation (Millsaps, 2017). By leveraging the support of industry, the Army created a 3D-printed grenade launcher and grenades that passed testing within 5% of actual grenade muzzle velocities (Mizokami, 2017). Building on their success with applied additive manufacturing, the Army developed a service specific roadmap that merged into the overarching DOD roadmap (Perrin, 2017).

3. DOD Challenges Associated with Additive Manufacturing

Additive manufacturing poses unique challenges both for the DOD as a whole and the individual services. This is a process that affects multiple areas within each service. Maintenance, supply, acquisitions, and legal components of each branch are involved with this endeavor. Three of the most salient issues are the replication of exact specifications, intellectual property rights, and the training of uniformed personnel.

a. Replication of Exact Specifications

Part verification and quality control remain critical areas of concern. According to an article in *National Defense Magazine*, the fact that 3D printed parts can vary from one iteration to the next exacerbates this existing condition (Harper, 2015). This becomes especially critical for parts required for flight operations, as every details from material density to surface finish is critical for safety and success (Harper, 2015). Additive manufacturing at sea magnifies these issues, as the sea states and water vapor adversely affect the leveling and internal ecosystem that make 3D printing possible (Harper, 2015).

b. Intellectual Property Rights

Many sources discuss intellectual property rights in depth, such as theses, *National Defense Magazine*, and the *Harvard Business Review*. Challenges associated with intellectual property rights include: securing Government access to required part files, protecting design owners, and structuring future acquisitions to account for these requirements (Muniz & Peters, 2016). A Naval Postgraduate School thesis titled "An Analysis of Additive Manufacturing Production Problems and Solutions" explores this topic more thoroughly (Muniz & Peters, 2016).

The practical application of additive manufacturing will require the transmission of data files. With this transmission, there is an inherent risk of cyber-attack. The possibility that outside entities could manipulate data files to disrupt military operations is a persistent threat (Harper, 2015).

A potential solution to both cyber security and intellectual property concerns lies in blockchain (also referred to as block and chain). *Harvard Business Review* defines blockchain as creating an environment where “contracts are embedded in digital code and stored in transparent, shared databases, where they are protected from deletion, tampering, and revision. In this world every agreement, every process, every task, and every payment would have a digital record and signature that could be identified, validated, stored, and shared” (Iansiti & Lakhani, 2017). As an emerging technology, blockchain still has a lot of ground to gain towards full market acceptance (Iansiti & Lakhani, 2017). For DOD application, SPAWAR is currently exploring a blockchain approach to additive manufacturing file storage and validation (K. Holzworth, personal communication, June 23, 2017).

c. Training of Uniformed Personnel

The final challenge with fully realizing the possibilities of additive manufacturing lies in the training of uniformed personnel. Training is necessary in design and engineering, machine operation, management and preparation of the raw materials, finishing of printed parts, and general supply chain knowledge (Joyce, Louis, & Seymour, 2014). Current additive manufacturing efforts include, and internally recruit, service members who seek the additional training, rather than utilizing a specific MOS (G. Pace, personal communication, June 21, 2017). This approach attracts the most motivated and brightest of minds. However, the approach lacks the depth and commonality of knowledge required for additive manufacturing to truly flourish (W. Jones, personal communication, June 21, 2017).

d. Way Forward

Answering the vast challenges associated with additive manufacturing internal to the DOD requires the employment of emerging technology with careful attention to detail. Defense Systems Information Analysis Center’s (DSIAC) article on the release of the DOD additive manufacturing roadmap highlights current capabilities and limitations (DSIAC, 2016). The article emphasized the necessity of improving four technical and four non-technical areas of concern: design, material, process, value chain, cultural change, workforce development, data management, and policy change (DSIAC, 2016). These eight criteria will serve as the “strategic document to identify areas of focus and address roadmap objectives" as the technology of tomorrow is applied to the warfighter of today (DSIAC, 2016). The reality of additive manufacturing as future enabler within the DOD was reinforced with the passing of the Department of Defense Authorization Bill on July 14, 2017 (Benedict, 2017). This bill included specific stipulations for additive manufacturing, including a mandate to "research and validate quality standards for 3D printed parts, and its plans to incorporate additive manufacturing into its depots, arsenals, and shipyards" (Benedict, 2017).

D. STATE OF ADDITIVE MANUFACTURING IN THE MARINE CORPS

The information available concerning additive manufacturing in the Marine Corps is just beginning to grow. This is a consequence of the specific nature of the topic and the immaturity of the technology within the service. There are three distinct areas where information is available: the Marine Corps' call to action, the Expeditionary Manufacturing Trailers, and the future of additive manufacturing in the Marine Corps.

1. Marine Corps Call to Action

The Senate Armed Services Committee has directed all of the Services to explore additive manufacturing (GAO, 2015). The Marine Corps responded to this call to action with three key documents. The first document was the Appleton Report. The second key document was Maradmin 489/16. Shortly thereafter, the Commandant of the Marine Corps communicated directly with the service expressing his intent. These documents form the basis for all action taken by the Marine Corps to date.

a. Appleton Report

The report by Appleton published in 2014, had three purposes: "(1) to provide a brief overview of the 3D printing industry, the technology, the applications and the materials; (2) to convey the rapid and accelerating pace of growth of the industry and (3) to outline the potential benefits to the Marine Corps" (Appleton, 2014, p. 2). This document introduces additive manufacturing, while simultaneously illustrating connections to the Marine Corps' mission.

The overview element of the report is simple enough for a non-technical reader to understand. At the same time, this portion covers enough to allow the reader to understand the state of the industry, capabilities and limitations of the technology, and projections for the future.

The report relies heavily on the analysis performed by Wohlers that year (Appleton, 2014). Wohlers is widely regarded as an industry subject matter expert for all things additive manufacturing. Basing projections on their data adds legitimacy to the process. Additionally, the report presented the Garter-Hype curve to illustrate expectations and disillusionment surrounding new technology (Appleton, 2014).

The three benefits addressed in the report are; inventory, transportation, and obsolescence (Appleton, 2014). The potential benefit for inventory is the reduction in necessary stocking levels, which is of paramount importance when considering space limitation on ship and expeditionary mission requirements (Appleton, 2014). Improvements with inventory will reduce the requirement to transport the same volume of repair parts. Often times, the majority of the cost associated with a repair part is the transportation of that part to the expeditionary user (Appleton, 2014). The report explains that additive manufacturing reduces the setup time required and the high penalties incurred, when manufacturing obsolete parts (Appleton, 2014).

b. Fragmentary Order 01/2016: Advance to Contact

In Fragmentary Order 01/2016, General Robert Neller, Commandant of the Marine Corps explicitly states his intent and desired endstate for the Marine Corps (United States Marine Corps, 2016a, p. 11). Within this order, General Neller outlined "five areas that are vital to achieving our future success" (United States Marine Corps, 2016a, p. 3). Of these five areas, three of them directly correlate to additive manufacturing. They are: "training/simulation/experimentation, integration with the Naval and Joint Forces, and modernization and technology" (United States Marine Corps, 2016a, p. 3). Additionally, the Commandant communicates three guiding principles interrelated to the aforementioned five areas (United States Marine Corps, 2016a). Additive manufacturing has a direct impact on two of these guiding principles. The first is “decentralizing the training and preparation for war, while adhering to Maneuver Warfare principles in the conduct of training and operations” (United States Marine Corps, 2016a, p. 3). The second principle is “Modernizing the Force, especially by leveraging new and evolving technologies” (United States Marine Corps, 2016a, p. 3).

To further illustrate his intent, General Neller gave the following guidance “In order to learn and improve, we will aggressively experiment, testing new concepts and capabilities, within existing training venues, and developing emerging venues where appropriate” (United States Marine Corps, 2016a, p. 8). The implications for logisticians and supply professionals are clear. The Commandant expects experimentation and modern solutions to the challenges of the constantly evolving battlefield.

The Commandant’s endstate clearly reiterates his intent that the force continues to modernize and maintain technological advantages over our adversaries. His endstate is to “field and operationalize ongoing programs and continue to develop solutions that will enhance institutional capabilities and retain our tactical advantages across the ROMO [Range of Military Operations] with today’s and tomorrow’s systems” (United States Marine Corps, 2016a, p. 11).

c. Maradmin 489/16

Lieutenant General Michael Dana, Deputy Commandant of Installation and Logistics Command, responded to the Commandant of the Marine Corps’ Fragmentary Order 01/16 by issuing Maradmin 489/16 in September of 2016. The purpose of this Maradmin was to “provide initial policy and guidance regarding the use of additive manufacturing (AM) equipment, design and fabrication processes for the production and use of AM-derived parts and other items” (United States Marine Corps, 2016b). This Maradmin authorizes the printing of any part with a source maintenance and recoverability code of M or X. The Maradmin further advises commands wanting to fabricate parts for operational equipment to request a waiver from MCSC (United States Marine Corps, 2016b). Commands are additionally encouraged to seek collaboration with Next Generation Logistics Innovation Cell – additive manufacturing if possible (United States Marine Corps, 2016b).

2. EXMAN Trailer

The literature surrounding the EXMAN trailer is currently limited to surface level information presenting the reader with concepts rather than critical details. This is due in large part to the cutting-edge nature of the program, and the Marines' consistent pursuit of innovation. 1st Maintenance Battalion accepted delivery of the EXMAN trailer in March 2016 (G. Pace, personal communication, February 12, 2017)[1]. The system debuted professionally during Operation Steel Knight from December 3, 2016 through December 13, 2016 (G. Pace, personal communication, February 12, 2017)[2]. The lack of published information forces interested parties to utilize promulgated slide shows, personal interviews, After Actions Reports (AARs), and articles generally written by Public Affairs.

Following the completion of Steel Knight 17, 1st Maintenance Battalion released a slide show within their professional community showing their progress from March to December of 2016 (G. Pace, personal communication, February 12, 2017)[3]. Personal interviews conducted with the Commanding Officer and subject matter experts of 1st Maintenance Battalion yielded additional information on the capabilities and limitations of the EXMAN trailer (G. Pace, personal communication, June 21, 2017). However, this information is not publicly available, and required direct communication with the Marines of 1st Maintenance Battalion.

The AAR for Steel Knight 17, published by Combat Logistics Regiment 1 (CLR-1) focused primarily on the exercise as a whole, and less on the specific details associated with the EXMAN trailer. The Marine Corps Center for Lessons Learned (MCCLL) published the AAR for major commands throughout the Marine Corps. The document is not intended to capture granular details, and omitted the fact that 1st Maintenance Battalion successfully printed 32 parts during the course of the exercise (United States Marine Corps, 2017b) (G. Pace, personal communication, June 21, 2017).

[1] Information communicated via a PowerPoint presentation titled EXMAN following USMC Exercise Steel Knight 2016.
[2] Ibid.
[3] Ibid.

3. Future of AM in the Marine Corps

Several theses from Naval Postgraduate School address the broad questions surrounding the future of additive manufacturing in the Marine Corps. This future is still uncertain in terms of scope and timeline. Focused details such as the use of 3D printed drones and the Marine Maker Movement are available in online articles. These sources, together with the actions of 1st and 2nd Maintenance Battalion, allow for some clarity regarding the future.

To date there have been two theses printed at the Naval Postgraduate School that address additive manufacturing in the Marine Corps. Captain Luke McLearen (USMC) wrote the first thesis in June of 2015. This thesis examines, "how additive manufacturing can improve the effectiveness of Marine Corps logistics" (McLearen, 2015, p. i). This thesis provides a comprehensive background on additive manufacturing as well as the benefits and challenges associated with implementing the technology. This thesis contributes to the decision to advance or delay implementation of additive manufacturing in the Marine Corps. In June of 2016, Captain Matthew Friedell (USMC) wrote a thesis on a similar topic. He examined the readiness of individual Marines to adopt new technology, specifically additive manufacturing (Friedell, 2016).

The adaptation of additive manufacturing to include Unmanned Aerial Systems (UAS) has drastically increased the practicability of the current technology. Examples of this innovative adaptation include the fixed wing UAS Scout, and the smaller rotary winged Nibbler. A Marine corporal designed Scout for easy disassembly, transport in a standard pack, and reassembly in a matter of minutes (Friedell, 2016). Fixed wing UAS normally cost around $130,000, but Scout costs approximately $600 (Friedell, 2016). Nibbler is a smaller rotary winged UAS that provides Maines an immediate ability for increased surveillance (Erwin, 2017). In addition to a comparatively lower cost, Nibbler has numerous design options. This allows the possibility of custom ordering a mission-specific solution the night before conducting operations (Erwin, 2017).

The Marine Corps has realized initial successes with additive manufacturing, and is seeking to exploit those successes in future endeavors. The chosen pathway to accomplishing this is through an adaptation of the Maker Movement, known as Marine Makers (Morrow, 2017). In order to make this a reality, Next Level Logistics have established Maker Labs at three Marine Corps installations. Each of these labs is comprised of the equipment and software necessary to train all interested Marines regardless of rank or MOS (Morrow, 2017). Additionally, a weeklong course known as Marine Maker Mobile Training instructs small cohorts of Marines in alternate and remote locations (Morrow, 2017).

E. CONCLUSION

The information available through applicable theses, studies, journal entries, newspaper articles, online articles, and industry reports decreases as the scope of the topic narrows. There is an abundance of information available about the relatively exciting and new industry of additive manufacturing. However, the literature available for additive manufacturing within the DOD is significantly less robust. Searching for literature regarding additive manufacturing within the Marine Corps yields far fewer results. However, the theses from Naval Postgraduate School do provide a reasonable background on the topic. The focused nature of these analyses offer tangible decision points for leadership within the Marine Corps.

IV. METHODOLOGY

A. INTRODUCTION

In order to determine the best value for the Marine Corps in terms of manufactured equipment parts, this CBA utilizes an *in medias res* approach. The intent of this CBA is to compare the incumbent, standard USMC supply chain acquisition method, to the alternate methods of 3D printing via Extrusion and CLIP. The costs include material and machine expenses for printed items as well as time savings. The OMB Circular A-94 and standard industry practices necessitate the monetization of these costs and benefits when possible (OMB, 1992). The CBA proposes a method to monetize time, as there is no generally accepted standard for time valuation.

B. COST-BENEFIT ANALYSIS METHODOLOGY

Analysts chose the type of CBA conducted based on the availability of data, desired level of decision-making, and position within the life cycle of the project. An *in medias res* analysis is conducted during the life of the project, and contrasts with an *ex ante* which is completed before beginning a project, and an *ex post* which is performed at the conclusion. Currently the Marine Corps is exploring additive manufacturing as a possible cost saving alternative of procuring equipment parts. Since this exploration of additive manufacturing alternatives is in progress, an *ex ante* or *ex post* approach is inappropriate. The ongoing nature of these initial steps into the rapidly advancing field of additive manufacturing necessitates the use of an *in medias res* for this CBA. This analysis compares currently available options of additive manufacturing in order to provide a decision-making framework on how to advance the Marine Corps' additive manufacturing capabilities.

There are many formats for an *in medias res* CBA. Each format employs a different numbers of steps. The following is a list of the nine steps this analysis utilizes, as found in *Cost-Benefit Analysis Concepts and Practice* (Boardman, Greenberg, Vining, & Weimer, 2011):

1. Specify the set of alternative projects.

2. Decide whose benefits and costs count (standing).

3. Identify the impact categories, catalogue them, and select measurement indicators.

4. Predict the impacts quantitatively over the life of the project.

5. Monetize (attach dollar values to) all impacts.

6. Discount benefits and costs to obtain present values.

7. Compute the net present value of each alternative.

8. Perform sensitivity analysis.

9. Make a recommendation. (Boardman et al., 2011, p. 6)

Each of these steps applies to the analysis in the following way:

Step 1. Specify the set of alternative projects: This CBA compares ordering through the traditional supply chain, current 3D printing with Extrusion machines, and 3D printing with CLIP technology.

Step 2. Decide whose benefits and costs count (standing): The standing for this CBA is strictly from the Marine Corps perspective. This CBA does not factor in the impact to industry or other DOD affiliated organizations such as Defense Logistics Agency (DLA).

Step 3. Identify the impact categories, catalogue them, and select measurement indicators: Impact categories for this CBA include the cost of printers, cost of print materials, printer maintenance, depreciation of assets, order and delivery time for OEM parts, and print times. The small sample size precludes the use of price for OEM parts. The variance is too high to extrapolate a baseline number with accuracy. This analysis intentionally excludes labor hours as a sunk cost. The Marines incur costs regardless of the task they are performing. Additionally, it is impossible to predict with accuracy how different units would employ those Marines. This remains a realized, but non-monetary benefit.

Step 4. Predict the impacts quantitatively over the life of the project: Realizing the impacts of each project extends beyond the immediate costs and benefits. To assess the alternatives accurately, the impacts must account for the full lifespan of the project. This entails a predictive element that estimates costs compounded over the total lifespan of the project. Examples include the total time for printing parts, and printer maintenance required throughout the life of the printer.

Step 5. Monetize (attach dollar values to) all impacts: In order to achieve accuracy in the comparison, the benefits and costs of each alternative must possess commonality. If the CBA compared cost in dollars, to benefits in hours, the effect would be a comparison of “apples and oranges.” This CBA achieves commonality by monetizing all impacts and using United States dollars as the basis for comparison.

Step 6. Discount benefits and costs to obtain present values: The difference in the value of a dollar over time degrades the commonality achieved by monetizing all costs and benefits. In order to correct this, all costs and benefits are converted and presented in 2017 dollars. This CBA utilizes the Naval Postgraduate School recommended discount rate of 7% in order to determine present value (S. Tick, personal communication, September 26, 2017). This accounts for the impact of inflation over time within the framework of the analysis. Due to the (high) expected usage rate, and the accelerated depreciation experienced by technology hardware, this CBA assumes a hardware value of zero after three years.

Step 7. Compute the net present value of each alternative: This summation captures the monetization and adjustment of all cost drivers in a single number. The single number is the net present value for each alternative. The sum of all benefits for each alternative minus the sum of all costs give the net present value in 2017 dollars. The economic formula for net present value is represented as NPV = PV (B) – PV (C) (Boardman et al., 2011), where

- NPV = Net Present Value
- PV (B) = Present Value of Benefits
- PV (C) = Present Value of Costs

Step 8. Perform sensitivity analysis. Uncertainty is part of any cost analysis (GAO, 2009). The difference in the assignment of values for a cost or benefit can have tremendous implications regarding the final net present value. To account for this transparently, it is important for analysts to present a range of values when estimating costs and benefits with the most risk (GAO, 2009). According to *Cost-Benefit Analysis Concepts and Practice,* "potentially, every assumption in a CBA can be varied. In practice one has to use judgment and focus on the most important assumptions" (Boardman et al., 2011, p. 15). This analysis presents four variations to reflect different initial investments and valuations of time.

Step 9. Make a recommendation: The basis for the recommendation relies solely on the analysis of the data available and the assumptions and methodology used in this analysis. The cost benefit analysis of each alternative compared with the status quo generates a net present value. The study uses net present values alone to derive recommendations.

C. TECHNICAL DATA

As indicated in Step 3, the sample size of comparative parts that can be either purchased or produced through additive manufacturing was too small to allow accurate pricing for OEM items. While the Marines at 1st Maintenance Battalion have produced more than 40 items using the EXMAN trailer, only 15 of them meet the criteria for future reproduction. That is, only 15 of the parts are directly associated with an item possessing a National Stock Number (NSN). Each one of those 15 parts has an associated CAD file and known data parameters. The Marines at 1st Maintenance Battalion provided those CAD files, as well as the associated print data based on actual printing orders completed with the Fortus 250mc (W. Jones, personal communication, September 26, 2017). This information was redacted and provided to Carbon 3D who filled out the estimated CLIP print data. This ensured that Carbon 3D was unaware of the times provided by the Marines at 1st Maintenance Battalion. This comparison resulted in an average print time of 242.5 minutes for an Extrusion produced part and 159.7 minutes for a CLIP manufactured part. Table 2 shows a full comparison of these 15 items with both Extrusion and CLIP considerations.

Table 2. Comparative Technical Data (CLIP and Extrusion)

Item Number	Part	Printed Length	Printed Width	Printed Height	Filament Material Length (Meters)	Extrusion Print Time (Minutes)	Material Volume (mL)	CLIP Print Time (Minutes)
1	AN/PVS17 C 17 Bridge	41.7	12.7	23.6	0.24	26	90	59
2	MK-19 Barrell Dust 40mm Plug	72.2	11.0	72.0	2.54	47	110	180
3	120mm Nut Tool	76.4	118.9	9.0	4.25	73	130	48
4	120mm Nut	58.0	57.7	9.0	1.67	76	100	44
5	1070 Wrench	184.3	198.4	49.3	29.12	685	320	620
6	BFT Cover Revision	120.9	10.2	29.5	1.70	71	110	72
7	Bridge Clamp Knob	47.5	47.2	46.0	8.63	147	150	115
8	Terrain Model	186.1	168.2	25.8	39.33	870	120	390
9	Castle Nut	150.0	175.0	50.0	79.72	134	90	20
10	Comm Knob	22.5	22.5	22.0	0.59	56	90	59
11	Helmet Arm 26 Degree Angle	68.1	27.4	11.1	0.70	32	100	32
12	Helmet Clip	24.0	12.0	5.0	0.09	6	90	17
13	HMMWV Clip	40.9	61.4	26.8	3.74	153	120	69
14	Impeller Fan	178.4	98.7	178.4	49.86	1237	550	458
15	M9 Guide Rod	10.5	10.5	91.0	0.67	25	100	213

D. VALUATION / MONETIZATION OF TIME

The most challenging impact to capture in this specific analysis is time. The supply system is capable of producing everything required with less investment in material, machines, and research when compared to either method of additive manufacturing. Similarly, Extrusion method 3D printing is less expensive than the CLIP method. The benefit each successive alternative offers is time in the form of speed of producing the needed part. The difference in having a part in two hours, eight hours, or 10 weeks is difficult to monetize yet is very important for the Marine Corps' mission success.

There are three reasons it is difficult to monetize time for this analysis. First, every maintenance situation is different. A door handle for an unarmored ambulance in garrison is not a critical item. An engine mount for a Mine Resistant Ambush Protected All-Terrain Vehicle (M-ATV) in a deployed environment may be much more critical.

The second and third order effects caused by not having an additional vehicle are difficult to capture with any degree of accuracy. Considerations include the following:

- Less dispersion (more Marines inside of a vehicle)
- Modifications to tactics, techniques, and procedures (TTPs) including immediate actions on enemy contact
- One less crew served weapon
- Reduced capacity to transport equipment and personnel

In the M-ATV scenario, the value of time required to obtain the repair part will be much higher.

The second reason for which valuation of time is difficult is that individual commanders value time differently. Even if the analysis examined repair parts based on TAMCN and priority code (1-15) as defined by the Uniform Material Movement and Issue Priority System (UMMIPS), the values would fluctuate drastically unit-to-unit. The individual unit valuation, based on unit specific TTPs and personal preference, is challenging to standardize. A support unit that never leaves the forward operating base (FOB) is less concerned with getting a M-ATV working than an infantry battalion is.

The final reason monetizing time is not easy is that the Marine Corps has not produced a significant number of parts using additive manufacturing. Gathering a statistically significant amount of data from the Marine Corps regarding parts produced through additive manufacturing, interviewing commanders, and using probability to establish a value range is not currently possible. Presently, a central data repository with National Item Identification Numbers, print time, materials, and end item is not available.

The U.S. Army (2013) provided guidance on "non-financial selection criteria" in its *U.S. Army Cost Benefit Analysis Guide*. Table 3 shows an example of this decision matrix. This matrix takes the total score for each course of action (COA) and multiplies it by a standardized cost (millions or thousands) to create a Cost-Benefit Index (United States Army, 2013). This method requires careful attention to detail and is highly subjective. In this instance, the example erroneously rated the value of Maintenance

Downtime for COA 1 higher than it should have. This small error gave COA 1 the edge over COA 2 before applying standardized cost (United States Army, 2013).

Table 3. Example of Decision Matrix to Evaluate Non-Financial Selection Criteria Source: United States Army (2013, p. 59).

		COA 1			COA 2			COA 3		
Criteria	**Weight**	**Data**	**Rating**	**Score**	**Data**	**Rating**	**Score**	**Data**	**Rating**	**Score**
Maintenance Downtime	.40	10 Hrs	9	3.6	7 Hrs	7	2.8	14 Hrs	4	1.6
Reduced Error Rate	.25	5 per 100	5	1.25	2.5 per 100	7	1.75	8 per 100	2	.50
Suitability	.20	Very Good	4	.80	Good	2	.40	Excellent	6	1.20
Improved Productivity	.15	240 per cycle	8	1.20	230 per cycle	7	1.05	200 per cycle	6	.90
Total Weight	**1.00**	**Total Score**		**6.85**	**Total Score**		**6**	**Total Score**		**4.2**

Our analysis considers four separate valuations of time. Due to data availability or concerns with applicability, the first two options are not viable. The analysis uses the third and fourth options, despite their shortcomings. This is for the sole purpose of establishing a standardization for the purpose of this CBA.

1. Valuation 1 (Rejected)

One option for valuation was to examine the total value or cost to replace all equipment of an infantry battalion Table of Organization and Equipment (TO/E). The infantry battalion is the basic structural building block within the Marine Corps. As such, the infantry battalion TO/E serves as a logical frame of reference. The TO/E shows fielded assets as well as planned assets. However, most infantry battalions are at less than 100% of the equipment they rate. According to the Global Combat Support System (GCSS), the actual value of an infantry battalion can range from $40 million (First Battalion, Sixth Marines as of September 20, 2017) to more than $130 million (First

Battalion, Sixth Marines circa 2012 in Afghanistan). The Marine Corps minimum acceptable level of readiness for equipment is 80%. This means that of the equipment on-hand at any given time, having 20% in maintenance is acceptable. Using this as a metric, the most the Marine Corps is willing to pay for maintenance is 20% of the value of the equipment. Dividing that total value by days in a year, and then hours in a day, shows what an infantry battalion pays for maintenance on an hourly basis. The logical stretch between required maintenance levels and a willingness to pay is too far for this method to be acceptable. At best, the rationale is dubious, and there are strong arguments that the logic is incorrect. The following is a notional example of this concept:

Notional account value: $100M

Acceptable readiness level: 80%

Gear nominally set aside for maintenance: 20%

Annual cost of maintenance: A = 20% * $100M

Daily cost of maintenance: D = A / 365 = $54,794.52

Hourly cost of maintenance: H = D / 24 = $2,283.11

This valuation method identifies the following logical fallacies. First, the Marine Corps structure does not support a unit operating indefinitely with 80% readiness. Marine Corps units certainly do not deploy with readiness this low. Secondly, the hourly valuation of maintenance (H) is for every item with a TAMCN owned by the unit. Not all TAMCNs are repairable, nor does this method provide a detailed valuation for a single broken asset. By this logic, a truck deadlined for three weeks (D * 21 days) represents $1.15 million in maintenance costs, which is clearly excessive. It is possible to divide the hourly valuation by the number of TAMCN items that a battalion owns. However, that number also appears incorrect. If you assume 4,000 repairable items, the hourly valuation of maintenance for a single item is $0.57 (H / 4,000). This means that the deadlined truck represents $287.28, which is clearly less than a commander would pay to have a vehicle for three weeks. This method is not accurate enough to use as a valuation of time.

2. Valuation 2 (Rejected)

Another option for the valuation of time was to examine the parts issued by the SMU for a geographic region. The SMU acts as the Marine Corps' local intermediate supply point; authorized to maintain items on-hand for issuance to units with a valid requirement. When a unit needs an item with a NSN, it places a GCSS requisition and creates a document number on the Due and Status File (DASF). The DASF routes all requests to the local SMU, and then to an external source of supply if necessary.

Conceivably, an analysis could examine total parts issued by the SMU over the course of a year to a specific unit to determine current Marine Corps willingness to pay for maintenance. An example of this would be the following:

Notional value of items issued from the SMU to Unit A:	\$450,000
Value of only repair parts issued:	A = \$375,000
Daily willingness to pay (for maintenance):	D = A / 365 = \$1,027.40
Hourly willingness to pay (for maintenance):	H = D / 24 = \$42.81

The glaring issue with this is that it only captures the actual amount paid by a unit for repair parts. There is no valuation of time beyond potential shipping costs. There is also no consideration for willingness to pay, or loss of capabilities due to broken equipment. An item ordered through the supply system via a NSN has a set price. The price does not change as priority changes. Additionally, narrowing down the information to show only repair parts would require a custom report within GCSS. While this information is theoretically possible to gather, it is beyond the scope of this analysis.

3. Valuation 3 (Preferred Method)

This method monetizes time by calculating the depreciation of deadlined items. By examining the depreciation rate of selected assets while simultaneously examining readiness, it is possible to monetize the value lost due to required maintenance. This valuation postulates that an asset in a ready status has value while an item in a deadlined status has no value in spite of the sunk costs.

This analysis used only items appearing on the 2017 Marine Corps Bulletin (MCBul) 3000. Items appearing in the MCBul 3000 are Marine Corps Automated Readiness Evaluation System (MARES) reportable items. "The intent of the MCBul 3000 is to capture the best sampling of equipment that represents the Marine Corps' ability to perform its mission" (United States Marine Corps, 2017c). The annual bulletin identified 231 principal end items (PEI) which "provide an adequate measure of overall equipment status and/or capability" (United States Marine Corps, 2017c). Additionally, the MCBul 3000 lists 93 PEIs as mission essential equipment (MEE). Assets are declared MEE when their "availability is essential and indispensable for the execution of the mission essential tasks (METs) of the unit" (United States Marine Corps, 2017c). This analysis utilized an Excel random number generator to select a sample of five items from each TAMCN family. This resulted in a total 25 PEIs from the MCBul 3000. Table 4 displays the distribution of the selected assets.

Table 4. Distribution of TAMCN Selection from MCBul 3000

ITEM	TAMCN	CATEGORY
1-5	A	Communications Asset
6-10	B	Engineering Asset
11-15	C	General Supplies
16-20	D	Vehicle Asset
21-25	E	Ordinance or Weapon

The analysis disqualified two TAMCNs (items 14 and 15), due to their being entirely composed of consumable items. If included, their lack of required maintenance disproportionately skews findings in favor of the incumbent system. Table 5 provides an overview of these 25 TAMCNs.

Table 5. MCBul 3000, GCSS, and TLCM-OST Sample Data

ITEM	TAMCN	ITEM NAME	MEE	USMC OWNED	Number DL	DL %	AVG Days DL	Service Life (Years)	Price	Weight	Weighted Days DL
1	A0067	AN/MRC-148	N	1529	164	10.73%	96	10	$ 53,234.00	9.66%	9.28
2	A0241	VSAT (M)	Y	65	11	16.92%	83	15	$ 90,000.00	0.41%	0.34
3	A0242	VSAT (L)	Y	119	20	16.81%	105	20	$ 295,000.00	0.75%	0.79
4	A0271	COC (V2)	N	12	0	0.00%	0	22	$ 4,950,000.00	0.08%	0.00
5	A3232	SMART-T	Y	41	7	17.07%	69	22	$ 825,000.00	0.26%	0.18
6	B0058	Mine Roller	N	506	8	1.58%	108	27	$ 45,000.00	3.20%	3.45
7	B0063	TRAM	Y	758	107	14.12%	78	14	$ 123,508.00	4.79%	3.74
8	B1045	100K Gen	N	522	21	4.02%	44	19	$ 67,000.00	3.30%	1.45
9	B1315	Launcher Clearance Mine	Y	63	7	11.11%	661	28	$ 150,000.00	0.40%	2.63
10	B2605	TWPS	Y	243	35	14.40%	84	20	$ 350,000.00	1.54%	1.29
11	C4549	Device, Propulsion Diver	N	182	5	2.75%	258	16	$ 77,270.00	1.15%	2.97
12	C5901	CRRC	N	465	17	3.66%	51	29	$ 10,500.00	2.94%	1.50
13	C6375	TORDS MTVS-421	Y	99	1	1.01%	29	19	$ 18,736.00	0.63%	0.18
16	D0022	HMMWV	N	1992	498	25.00%	92	23	$ 186,729.00	12.59%	11.58
17	D0025	MRAP	Y	1097	70	6.38%	55	11	$ 705,421.00	6.93%	3.81
18	D0036	MAT-V	Y	622	140	22.51%	55	21	$ 575,000.00	3.93%	2.16
19	D1063	HIMAR	N	104	12	11.54%	217	34	$ 404,397.71	0.66%	1.43
20	D1214	Wrecker (LVSR)	Y	94	28	29.79%	63	24	$ 1,013,405.24	0.59%	0.37
21	E0055	SABER	Y	676	28	4.14%	41	19	$ 970,000.00	4.27%	1.75
22	E0207	Javelin	Y	425	37	8.71%	153	26	$ 133,063.00	2.69%	4.11
23	E0980	M2	N	4080	53	1.30%	59	68	$ 8,118.00	25.78%	15.21
24	E1095	81mm Mortar	Y	941	45	4.78%	65	30	$ 133,500.00	5.95%	3.87
25	E1460	M40A5	N	1189	9	0.76%	30	25	$ 7,503.05	7.51%	2.25
TOTAL	-	-	13	15824	1323	-	-	542	$ 11,192,385.00	100.00%	74.34
AVERAGE	-	-	-	688	57.52	9.96%	108.52	23.57	$ 486,625.43	4.35%	3.23
~~14~~	~~C8624~~	~~AMAL 631~~	~~N~~	~~56~~	~~0~~	~~0.00%~~	~~0~~	~~-~~	~~$ 562,533.81~~	~~0.00%~~	~~0.00~~
~~15~~	~~C8745~~	~~AMAL 645~~	~~N~~	~~32~~	~~0~~	~~0.00%~~	~~0~~	~~-~~	~~$ 991,305.36~~	~~0.00%~~	~~0.00~~

The data in Table 5 is derived from GCSS, Total Life Cycle Management – Operational Support Tool (TLCM-OST), and technical manuals. The USMC-owned column denotes the total number of the associated TAMCNs owned by the Marine Corps. Number deadlined (DL) represents the total number of each TAMCN that is not available for use as of September 21, 2017. Dividing the number of assets deadlined by the total owned calculates deadlined percentage. Average days deadlined was obtained via TLCM-OST, which is fed by the Total Force Structure Management System (TFSMS) and GCSS-MC. The analysis used technical manuals and/or TLCM-OST to provide service life data. However, it is important to note that TLCM-OST has a Program Level focus. The source for the price was also TLCM-OST. Weight was determined by dividing the total number of each individual asset owned by the sum of all (23) assets owned. This ensures that all data derived is proportionately weighted. The calculation for weighted days deadlined is weight multiplied by average days deadlined for each individual TAMCN.

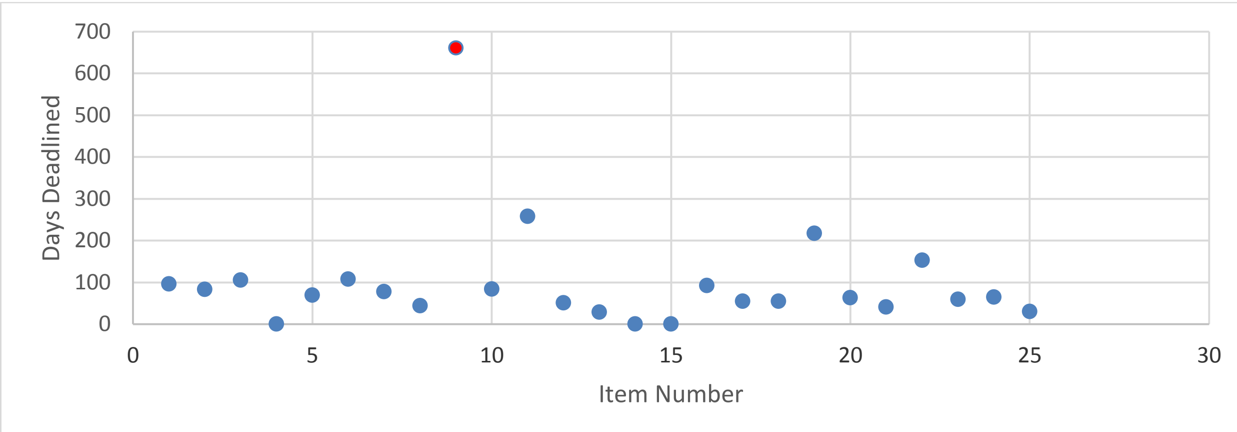
A cursory examination of the data reveals a daily depreciation cost of $56.56 on average. The data also shows an average deadline length of 108.52 days. The calculations used to determine these values are as follows:

Average value of MCBul 3000 asset:	V = $486,625.43
Average days a MCBul 3000 asset is Deadlined:	DL = 108.52 Days
Average lifespan of MCBul 3000 asset:	LS = 23.57 Years
Average annual depreciation of asset:	AD = V / LS = $20,645.97
Daily average depreciation:	DD = AD / 365 = $56.56
Hourly average depreciation:	HD = DD / 24 = $2.36
Average depreciation per PEI failure:	DL * DD = $6,137.89

After the initial review, it was determined that B1315 is disproportionately weighted. Removal of this outlier further refines the data, providing additional accuracy. Table 6 shows the distribution of days deadlined by TAMCN. The red dot denotes B1315, which is inconsistent with the rest of the data points. The Marine Corps owns

(63) B1315s. This represents 0.4% of the assets analyzed, and causes a 25.12-day increase in average days deadlined.

Table 6. Days Deadlined by Item Number



When B1315 (red data point) is absent, the average days deadlined drops to 83.41 days. Using the weighted average to determine the number of days deadlined further demonstrates the inaccuracy of this point. The true average declines to 74.34 days when assigning a weight to each TAMCN. This also changes the value analysis to reflect an average depreciation per PEI failure cost of $4,204.67 versus the original $6,137.89. The calculations used to determine this value are as follows:

Average value of MCBul 3000 asset:	V = $486,625.43
Weighted average days an asset is deadlined:	DL = 74.34 Days
Average lifespan of McBul 3000 asset:	LS = 23.57 Years
Average annual depreciation of asset:	AD = V / LS = $20,645.97
Daily average depreciation:	DD = AD / 365 = $56.56
Hourly average depreciation:	HD = DD / 24 = $2.36
Average depreciation per PEI failure:	DL * DD = $4,204.67

Table 7 shows the statistical impact of removing B1315. The mean (average days deadlined) drops by 25 (108 to 83) and the margin of error is reduced from 57 to 26. Both data sets assume a confidence level of 95%. The minimum for both data sets remains at zero despite the removal of C8624 and C8745. TLCM-OST reports zero average days deadlined for A0271. However, the asset was included in the analysis because the asset does require regular, and at times extensive, maintenance of sub-components (Stock List Three equipment).

Table 7. Descriptive Statistics of Sample Data

All 23 Data Points	
Mean	108.52
Standard Error	27.90
Median	69.00
Mode	55.00
Standard Deviation	133.82
Sample Variance	17907.08
Skewness	3.52
Range	661.00
Minimum	0.00
Maximum	661.00
Sum	2496.00
Count	23.00
Confidence Level(95.0%)	57.87

22 Data Points (without B1315)	
Mean	83.41
Standard Error	12.73
Median	67.00
Mode	55.00
Standard Deviation	59.70
Sample Variance	3564.25
Skewness	1.71
Range	258.00
Minimum	0.00
Maximum	258.00
Sum	1835.00
Count	22.00
Confidence Level(95.0%)	26.47

For the purpose of this CBA, the analysis assumes 14 days for initial part requirement identification and repairs after receipt of the necessary part. The calculated cost of this time is $792.96 (14 days * $2.36/hour). Using the framework provided each item printed will save the Marine Corps $3,411.71 ($4,204.67 - $792.96) minus the time required to print (at a rate of $2.36 per hour). This valuation method is conservative and only captures depreciation or value lost due to not having the required parts for maintenance. This valuation assumes a constant rate of applied maintenance independent of part lead times. The basis of the depreciation analysis is solely the critical items listed in the MCBul 3000, which represents only a small portion of total TAMCNs within the Marine Corps. The conservative nature of this method does not capture any willingness to pay associated with the deadlined equipment.

4. Valuation 4 (Less Preferred Method)

On June 17, 2010 the DOD Inspector General released report D-2010-068 (DOD IG, 2010). This report highlights oversight issues associated with contracted maintenance for the newly fielded Mine Resistant Ambush Protected (MRAP) vehicle. D-2010-068 covers the period of November 2006 to November 2009 (DOD IG, 2010). The data show what MCSC paid to five contractors providing field service representatives (FSRs), and instructors during that period. This valuation used the amount paid ($815 million) to approximate what the Marine Corps' willingness to pay was for maintenance (DOD IG, 2010). This does not mean that the Marine Corps is unwilling to pay more, or that the contracts were fair and reasonable. The only assertion is that the Marine Corps paid this amount for maintenance, and therefore critical maintenance is worth at least that amount to the Marine Corps. Table 8 provides a summary of the data provided by D-2010-068 with additional columns added for analysis.

Table 8. D-2010-068 Selected Data. Adapted from DOD IG (2010)

Contractor	Man-months	Total Obligated Amount	Monthly Fee	Daily Fee	Hourly Fee
GDLS-C	1890	$65,123,662.00	$34,456.96	$1,133.45	$47.23
BAE-TVS	2966	$99,466,859.00	$33,535.69	$1,103.15	$45.96
BAE-TVS	3471	$132,139,047.00	$38,069.45	$1,252.28	$52.18
FPII	7991	$200,315,445.00	$25,067.63	$824.59	$34.36
NaviStar	7995	$318,394,078.00	$39,824.15	$1,310.00	$54.58
Total	24313	$815,439,091.00	-	-	-
Average	4862.60	$163,087,818.20	$33,539.22	$1,103.26	$45.97

The term *man-month* "is a unit of measure that represents one FSR or Instructor under contract performing services for one month" (DOD IG, 2010, p.10). The report does not provide a clear delineation between FSR and instructor rates. As a result, this valuation uses an average of total man-months and total contract amount. D-2010-068 provides total man-months and total obligated amounts. The analysis used the following calculations in order to complete the table:

Monthly fee: Total obligated amount / Man-months

Daily fee: Monthly fee / 30.4

Hourly fee: Daily fee / 24

The calculated weighted average for each maintenance hour is \$45.97. The \$45.97 is not a direct average, but rather a weighted average correlating the hours of each contract to rates paid in order to determine the average amount charged to the Marine Corps. Also, this 24-hour day design is intentional. The assumption is that contractors were reimbursed based on a pre-negotiated salary, vice an hourly wage. Any time spent in Afghanistan or Iraq as a contractor is working hours. If the hourly fee were calculated using a 12- or 16-hour day, the rate would be substantially higher. This valuation encompasses the Marine Corps' willingness to pay for each hour for a critical TAMCN during combat operations. This is not necessarily indicative of the Marine Corps' general willingness to pay for non-critical assets. However, this is appropriate for establishing the value of time for high-demand assets.

V. COST-BENEFIT ANALYSIS

A. INTRODUCTION

This chapter presents the relevant data gathered through research and the analysis, utilizing the aforementioned methodology. The Cost Benefit Analysis monetizes costs and benefits, adjusts for inflation, and compares net present values in 2017 dollars. This comparison, coupled with a sensitivity analysis, provides a functional decision-making foundation.

The analysis conforms to the following steps, listed in the "Methodology" chapter:

1. Specify the set of alternative projects.
2. Decide whose benefits and costs count (standing).
3. Identify the impact categories, catalogue them, and select measurement indicators.
4. Predict the impacts quantitatively over the life of the project.
5. Monetize (attach dollar values to) all impacts.
6. Discount benefits and costs to obtain present values.
7. Compute the net present value of each alternative.
8. Perform sensitivity analysis.
9. Make a recommendation. (Boardman et al., 2011, p. 6)

The analysis consists of four separate segments; baseline, sensitivity of valuation of time, sensitivity of estimated days deadlined, and sensitivity of initial investment.

B. COST BENEFIT ANALYSIS

The individual analyses presented are operationalized in Excel tables. This chapter explains the analysis represented in each table. The framework provided in the "Methodology" chapter, the introduction to this chapter, and subsequent paragraphs deliver this explanation.

1. Baseline Analysis

This analysis assigns the incumbent (OEM), which is the accepted standard, with a baseline value of zero, as shown in Table 9. The alternatives displayed are Extrusion and CLIP. This comparison forgoes conducting an analysis of OEM due to a lack of data. Also, it is standard practice to monetize marginal costs and savings for each alternative relative to the status quo (Boardman et al., 2011). There are more than 17 million registered NSNs available for order (NSN Center, 2017). The data associated with verified 3D printable parts would not be statistically significant. Therefore, OEM would only possess a negative value in response to the valuation of time, which would be misleading.

Table 9. Baseline CBA (Net Value)

EXTRUSION						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 3,742,335.07	$ 3,742,335.07	$ 3,742,335.07	$ 11,227,005.22
Total Benefits		$ -	$ 3,742,335.07	$ 3,742,335.07	$ 3,742,335.07	$ 11,227,005.22
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (45,000.00)	$ -	$ -	$ -	$ (45,000.00)
	Printer Materials		$ (8,827.78)	$ (8,827.78)	$ (8,827.78)	$ (26,483.34)
	Printer Maintenance	$ -	$ (6,200.00)	$ (6,200.00)	$ (6,200.00)	$ (18,600.00)
Total Costs		$ (45,000.00)	$ (15,027.78)	$ (15,027.78)	$ (15,027.78)	$ (90,083.34)
Annual NV		$ (45,000.00)	$ 3,727,307.29	$ 3,727,307.29	$ 3,727,307.29	
TOTAL NV						$ 11,136,921.87

CLIP						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 5,987,736.12	$ 5,987,736.12	$ 5,987,736.12	$ 17,963,208.35
Total Benefits		$ -	$ 5,987,736.12	$ 5,987,736.12	$ 5,987,736.12	$ 17,963,208.35
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (50,000.00)	$ (50,000.00)	$ (50,000.00)	$ -	$ (150,000.00)
	Printer Materials	$ -	$ (39,257.06)	$ (39,257.06)	$ (39,257.06)	$ (117,771.19)
	Printer Maintenance	$ -	$ -	$ -	$ -	$ -
Total Costs		$ (50,000.00)	$ (89,257.06)	$ (89,257.06)	$ (39,257.06)	$ (267,771.19)
Annual NV		$ (50,000.00)	$ 5,898,479.05	$ 5,898,479.05	$ 5,948,479.05	
TOTAL NV						$ 17,695,437.15

Impact categories for this analysis include:

Value of time saved: The “Methodology” chapter covers the rationale for this valuation in depth. The value assigned for every hour saved is $2.36, which results in an average of $3,417.66 saved for every part printed.

Cost of the printer: For the Fortus 250mc the price is set at $45,000, which is consistent with what the Marine Corps paid, and the stated price within the *Wohlers Report* (Wohlers et al., 2017). The price for Carbon 3D’s M2 is set at $50,000 per year, via a service contract, with a minimum of three years. This is consistent with communications with Carbon 3D (J. Rolland, personal communication, September 14, 2017).

Cost of the materials: The price of raw materials for CLIP are a direct quote from the Carbon 3D sales representative (J. Rolland, personal communication, September 14, 2017). The price of raw materials for Extrusion are from the cheapest available commercial source, based on market research (AET Labs, 2017). The amount of materials used are based on a direct comparison of what the Marine Corps used to print parts, and what Carbon 3D has estimated they would use to print the exact same parts (J. Rolland, personal communication, September 27, 2017). Sanitized cost tables were provided to Carbon 3D in order to facilitate this direct comparison. Carbon 3D did not have access to the Marine Corps printing data.

Cost of printer maintenance: The cost of printer maintenance is zero for CLIP machines. The service contract includes spare parts and maintenance. The cost of maintenance for the Fortus 250mc is what the Marine Corps is currently paying to GoEngineer for annual maintenance (W. Jones, personal communication, October 6, 2017).

Available print time per day: The available print time per day is set to 12 hours to minimize the potential benefits and provide the most pessimistic approach. Increasing the available print time per day would measurably increase benefits. In a deployed environment Marines could use the printers in shifts and print up to 20 hours per day. However, in a non-deployed environment this level of operation is unlikely. When factoring in maintenance and training, 12 hours per day is a reasonable assumption.

Table 10 provides the full explanation of these values. This table outlines the metrics associated with each component of the CBA.

Table 10. Calculations and Valuations for Baseline CBA.

Extrusion		
Available print time per day	12	Hours
Time required to print	4	Hours
Parts printed per day	3	Parts
Days printing per year	365	Days
Parts printed per year	1095	Parts
Average material per part	3.49	Cubic Inches
Cost per cubic inch	$2.31	Per Cubic Inch
Average material cost per part	$8.06	Per Part
CLIP		
Available print time per day	12	Hours
Time required to print	2.5	Hours
Parts printed per day	4.8	Parts
Days printing per year	365	Days
Parts printed per year	1752	Parts
Average material per part	149.38	Mililiters
Cost per milliliter	$0.15	Per ML
Average material cost per part	$22.41	Per Part
Value of Time Per Part		
Average time DL	74.34	Days
Inspection time required	7	Days
Install time required	7	Days
Time saved by printing	60.34	Days
Hourly depreciation rate	$2.36	Per Hour
Daily depreciation rate	$56.64	Per Day
Value of time saved	$3,417.66	Per Item

The initial net value for each alternative is positive. For Extrusion, the net benefit is $11.1 million. CLIP carries a net benefit of $17.7 million. The initial analysis compares costs and benefits across three years as equal units of measure. However, the value of money diminishes over time. In order to achieve a true comparison, the future value of money requires discounting. This cumulative discounted value is net present value (NPV). The discount rate assigned for this analysis is 7%, which is consistent with Naval Postgraduate School curriculum. (S. Tick, personal communication, September 26, 2017). Table 11 shows the impact of applying the discount rate.

Table 11. Baseline CBA Net Present Value (NPV)

EXTRUSION						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 3,497,509.41	$ 3,268,700.39	$ 3,054,860.17	$ 9,821,069.97
Total Benefits		$ -	$ 3,497,509.41	$ 3,268,700.39	$ 3,054,860.17	$ 9,821,069.97
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (45,000.00)	$ -	$ -	$ -	$ (45,000.00)
	Printer Materials	$ -	$ (8,250.26)	$ (7,710.53)	$ (7,206.10)	$ (23,166.89)
	Printer Maintenance	$ -	$ (5,794.39)	$ (5,415.32)	$ (5,061.05)	$ (16,270.76)
Total Costs		$ (45,000.00)	$ (14,044.65)	$ (13,125.85)	$ (12,267.15)	$ (84,437.65)
Annual NPV		$ (45,000.00)	$ 3,483,464.76	$ 3,255,574.54	$ 3,042,593.03	
TOTAL NPV						$ 9,736,632.33

CLIP						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 5,596,015.06	$ 5,229,920.62	$ 4,887,776.28	$ 15,713,711.96
Total Benefits		$ -	$ 5,596,015.06	$ 5,229,920.62	$ 4,887,776.28	$ 15,713,711.96
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (50,000.00)	$ (46,728.97)	$ (43,671.94)	$ -	$ (140,400.91)
	Printer Materials	$ -	$ (36,688.84)	$ (34,288.64)	$ (32,045.46)	$ (103,022.94)
	Printer Maintenance	$ -	$ -	$ -	$ -	$ -
Total Costs		$ (50,000.00)	$ (83,417.82)	$ (77,960.58)	$ (32,045.46)	$ (243,423.85)
Annual NPV		$ (50,000.00)	$ 5,512,597.24	$ 5,151,960.04	$ 4,855,730.82	
TOTAL NPV						$ 15,470,288.11

Applying the 7% discount rate across each year's costs and benefits allows for the comparison of alternatives in 2017 dollars. The resulting NPV of Extrusion is $9.7 million. The NPV of CLIP is $15.5 million. With these parameters and metrics, CLIP is superior to Extrusion. However, the parameters used to derive these numbers do carry a meaningful level of sensitivity. In order to explore and demonstrate the extent of the variability, we present the following sensitivity analyses: reduced value of time, reduced length of average days deadlined, and change of the amount of Extrusion machines purchased to match the initial investment of CLIP.

2. Sensitivity of Results to Valuation of Time

The value of time saved is the most significant factor used to determine which method provides the most benefit. The alternate valuation presented in the "Methodology" chapter shows a value 19 times higher than the baseline CBA value. The alternate value and the baseline value both provide an overwhelming argument in favor of additive manufacturing. Given the difficulty in determining an accurate valuation of time, this analysis examines a greatly reduced rate. This provides the decision maker a range of values, including the most pessimistic valuation of time (benefits). For the purpose of this sensitivity analysis, the value of time changes from $2.36 an hour to $1.00 per hour, a reduction of 58%. Table 12 captures the parameters of this alternative and Table 13 provides the discounted analysis.

Table 12. Calculations Parameters for Valuation of Time Sensitivity Analysis

Extrusion		
Available print time per day	12	Hours
Time required to print	4	Hours
Parts printed per day	3	Parts
Days printing per year	365	Days
Parts printed per year	1095	Parts
Average material per part	3.49	Cubic Inches
Cost per cubic inch	$2.31	Per Cubic Inch
Average material cost per part	$8.06	Per Part
CLIP		
Available print time per day	12	Hours
Time required to print	2.5	Hours
Parts printed per day	4.8	Parts
Days printing per year	365	Days
Parts printed per year	1752	Parts
Average material per part	149.38	Milliliters
Cost per milliliter	$0.15	Per ML
Average material cost per part	$22.41	Per Part
Valuation of Time Per Part		
Average time DL	74.34	Days
Inspection time required	7	Days
Install time required	7	Days
Time saved by printing	60.34	Days
Hourly depreciation rate	$1.00	Per Hour
Daily depreciation rate	$24.00	Per Day
Value of time saved	$1,448.16	Per Item

Table 13. Valuation of Time Sensitivity Analysis NPV

EXTRUSION						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 1,481,995.51	$ 1,385,042.54	$ 1,294,432.28	$ 4,161,470.33
Total Benefits		$ -	$ 1,481,995.51	$ 1,385,042.54	$ 1,294,432.28	$ 4,161,470.33
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (45,000.00)	$ -	$ -	$ -	$ (45,000.00)
	Printer Materials	$ -	$ (8,250.26)	$ (7,710.53)	$ (7,206.10)	$ (23,166.89)
	Printer Maintenance	$ -	$ (5,794.39)	$ (5,415.32)	$ (5,061.05)	$ (16,270.76)
Total Costs		$ (45,000.00)	$ (14,044.65)	$ (13,125.85)	$ (12,267.15)	$ (84,437.65)
Annual NPV		$ (45,000.00)	$ 1,467,950.86	$ 1,371,916.69	$ 1,282,165.13	
TOTAL NPV						$ 4,077,032.68

CLIP						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 2,371,192.82	$ 2,216,068.06	$ 2,071,091.64	$ 6,658,352.52
Total Benefits		$ -	$ 2,371,192.82	$ 2,216,068.06	$ 2,071,091.64	$ 6,658,352.52
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (50,000.00)	$ (46,728.97)	$ (43,671.94)	$ -	$ (140,400.91)
	Printer Materials	$ -	$ (36,688.84)	$ (34,288.64)	$ (32,045.46)	$ (103,022.94)
	Printer Maintenance	$ -	$ -	$ -	$ -	$ -
Total Costs		$ (50,000.00)	$ (83,417.82)	$ (77,960.58)	$ (32,045.46)	$ (243,423.85)
Annual NPV		$ (50,000.00)	$ 2,287,775.01	$ 2,138,107.48	$ 2,039,046.19	
TOTAL NPV						$ 6,414,928.67

Applying the reduced valuation of time diminishes the value of both alternatives. The NPV for Extrusion is $4.1 million, a reduction of $5.6 million from the baseline CBA. The NPV for CLIP is $6.4 million, a reduction of $9.1 million from the baseline CBA. In this instance, both methods retain a positive value. The change affects CLIP more severely, although it remains the most beneficial by a margin of $2.4 million. The lowest value of time, providing a positive benefit for both alternatives is $0.04 (per hour). This is in stark contrast to the highest demonstrated willingness to pay of $45.97 (per hour).

3. Sensitivity of Results to Estimated Days Deadlined

The amount of days deadlined (DDL) is the second largest impact category, following only the valuation of time. The "Methodology" chapter provides an in-depth explanation of the amount of average days deadlined utilized in the baseline CBA. The intention of this sensitivity analysis is to capture the benefits derived from a greatly reduced average DDL. This sensitivity analysis reduces the DDL from 74.34 to 35, a reduction of 53%. Table 14 captures the parameters for this valuation, and Table 15 shows the discounted analysis.

Table 14. Calculation Parameters for Reduced DDL Sensitivity Analysis

Extrusion		
Available print time per day	12	Hours
Time required to print	4	Hours
Parts printed per day	3	Parts
Days printing per year	365	Days
Parts printed per year	1095	Parts
Average material per part	3.49	Cubic Inches
Cost per cubic inch	$2.31	Per Cubic Inch
Average material cost per part	$8.06	Per Part
CLIP		
Available print time per day	12	Hours
Time required to print	2.5	Hours
Parts printed per day	4.8	Parts
Days printing per year	365	Days
Parts printed per year	1752	Parts
Average material per part	149.38	Milliliters
Cost per milliliter	$0.15	Per ML
Average material cost per part	$22.41	Per Part
Value of Time Per Part		
Average time DL	35	Days
Inspection time required	7	Days
Install time required	7	Days
Time saved by printing	21	Days
Hourly depreciation rate	$2.36	Per Hour
Daily depreciation rate	$56.64	Per Day
Value of time saved	$1,189.44	Per Item

Table 15. Reduced DDL Sensitivity Analysis NPV

EXTRUSION						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 1,217,230.65	$ 1,137,598.74	$ 1,063,176.39	$ 3,418,005.79
Total Benefits		$ -	$ 1,217,230.65	$ 1,137,598.74	$ 1,063,176.39	$ 3,418,005.79
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (45,000.00)	$ -	$ -	$ -	$ (45,000.00)
	Printer Materials	$ -	$ (8,250.26)	$ (7,710.53)	$ (7,206.10)	$ (23,166.89)
	Printer Maintenance	$ -	$ (5,794.39)	$ (5,415.32)	$ (5,061.05)	$ (16,270.76)
Total Costs		$ (45,000.00)	$ (14,044.65)	$ (13,125.85)	$ (12,267.15)	$ (84,437.65)
Annual NPV		$ (45,000.00)	$ 1,203,186.00	$ 1,124,472.90	$ 1,050,909.25	
TOTAL NPV						$ 3,333,568.15

CLIP						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 1,947,569.05	$ 1,820,157.99	$ 1,701,082.23	$ 5,468,809.27
Total Benefits		$ -	$ 1,947,569.05	$ 1,820,157.99	$ 1,701,082.23	$ 5,468,809.27
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (50,000.00)	$ (46,728.97)	$ (43,671.94)	$ -	$ (140,400.91)
	Printer Materials	$ -	$ (36,688.84)	$ (34,288.64)	$ (32,045.46)	$ (103,022.94)
	Printer Maintenance	$ -	$ -	$ -	$ -	$ -
Total Costs		$ (50,000.00)	$ (83,417.82)	$ (77,960.58)	$ (32,045.46)	$ (243,423.85)
Annual NPV		$ (50,000.00)	$ 1,864,151.23	$ 1,742,197.41	$ 1,669,036.77	
TOTAL NPV						$ 5,225,385.41

Reducing the DDL diminishes the value of both alternatives. The NPV for Extrusion is $3.3 million, a reduction of $6.4 million from the baseline CBA. The NPV for CLIP is $5.2 million, a reduction of $10.2 million from the baseline CBA. Both methods continue to retain a positive value. This change also affects CLIP more severely, although it remains the most beneficial by a margin of $1.9 million. This sensitivity analysis captures the reduced benefits that would occur from a doubling of the effectiveness of current Marine Corps maintenance. The lowest value of DDL that still provides a positive return for each alternative is 15 days. These 15 days include the 14 days taken for initial inspection and time required to make repairs. As long as 3D printing saves one day when compared to OEM, these models predict a positive return on investment.

4. Sensitivity of Results to Initial Investment

The baseline CBA presents a direct comparison of one Fortus 250mc (Extrusion) to one Carbon M2 (CLIP). This results in an unequal initial investment in terms of monetary cost. To narrow this disparity, this analysis compares two Fortus 250mcs to one Carbon M2. This results in a total expenditure of $90,000 for the Fortus machines and $140,000 (discounted) over the life of the single Carbon machine. The anticipated maintenance costs associated with the Fortus machines further narrows the gap. Table 16 captures the parameters for this analysis, and Table 17 shows the discounted value.

Table 16. Calculation Parameters for Equalized Initial Investment

Extrusion		
Available print time per day	12	Hours
Time required to print	4	Hours
Parts printed per day	6	Parts
Days printing per year	365	Days
Parts printed per year	2190	Parts
Average material per part	3.49	Cubic Inches
Cost per cubic inch	$2.31	Per Cubic Inch
Average material cost per part	$8.06	Per Part
CLIP		
Available print time per day	12	Hours
Time required to print	2.5	Hours
Parts printed per day	4.8	Parts
Days printing per year	365	Days
Parts printed per year	1752	Parts
Average material per part	149.38	Milliliters
Cost per milliliter	$0.15	Per ML
Average material cost per part	$22.41	Per Part
Value of Time per Part		
Average time DL	74.34	Days
Inspection time required	7	Days
Install time required	7	Days
Time saved by printing	60.34	Days
Hourly depreciation rate	$2.36	Per Hour
Daily depreciation rate	$56.64	Per Day
Value of time saved	$3,417.66	Per Item

Table 17. Equalized Initial Investment Sensitivity Analysis NPV

EXTRUSION						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 6,995,018.83	$ 6,537,400.77	$ 6,109,720.35	$ 19,642,139.95
Total Benefits		$ -	$ 6,995,018.83	$ 6,537,400.77	$ 6,109,720.35	$ 19,642,139.95
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (90,000.00)	$ -	$ -	$ -	$ (90,000.00)
	Printer Materials	$ -	$ (16,500.52)	$ (15,421.05)	$ (14,412.20)	$ (46,333.77)
	Printer Maintenance	$ -	$ (11,588.79)	$ (10,830.64)	$ (10,122.09)	$ (32,541.52)
Total Costs		$ (90,000.00)	$ (28,089.31)	$ (26,251.69)	$ (24,534.29)	$ (168,875.29)
Annual NPV		$ (90,000.00)	$ 6,966,929.52	$ 6,511,149.08	$ 6,085,186.06	
TOTAL NPV						$ 19,473,264.66

CLIP						
Category	Item	Year 0	Year 1	Year 2	Year 3	Total
Benefits	Time Saved in $	$ -	$ 5,596,015.06	$ 5,229,920.62	$ 4,887,776.28	$ 15,713,711.96
Total Benefits		$ -	$ 5,596,015.06	$ 5,229,920.62	$ 4,887,776.28	$ 15,713,711.96
Costs	OEM Parts	$ -	$ -	$ -	$ -	$ -
	Printers	$ (50,000.00)	$ (46,728.97)	$ (43,671.94)	$ -	$ (140,400.91)
	Printer Materials	$ -	$ (36,688.84)	$ (34,288.64)	$ (32,045.46)	$ (103,022.94)
	Printer Maintenance	$ -	$ -	$ -	$ -	$ -
Total Costs		$ (50,000.00)	$ (83,417.82)	$ (77,960.58)	$ (32,045.46)	$ (243,423.85)
Annual NPV		$ (50,000.00)	$ 5,512,597.24	$ 5,151,960.04	$ 4,855,730.82	
TOTAL NPV						$ 15,470,288.11

Altering the initial investment to provide two Fortus machines dramatically changes the analysis. The resulting NPV of Extrusion is $19.5 million. The NPV of CLIP remains $15.5 million. With these parameters and metrics, Extrusion is superior to CLIP.

5. Summary of Cost Benefit Analysis Findings

In every analysis and sensitivity test, both methods provided positive total NPV. Even when adjusted for the most conservative values ($1.00 per hour for time, 35 DDL) the models show a positive NPV. This analysis shows Carbon's M2 provides the most value when examining a direct comparison of one Fortus 250mc to one Carbon M2. However, the Fortus 250mc provides more benefit when comparing two machines to a single Carbon M2.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSION

A. RESEARCH INTENT

The purpose of this analysis was to compare the current method of obtaining OEM parts via the supply system to the available additive manufacturing alternatives. These alternatives included the currently utilized method of Extrusion and the emerging technology of CLIP. The following are the specific research questions addressed by this thesis:

- Is additive manufacturing a cost reducing option for the Marine Corps, compared to acquiring OEM items from the established Supply Chain?
- When comparing the additive manufacturing alternatives, which is more cost efficient for the Marine Corps to use Extrusion Printing or CLIP?

Currently, the Marine Corps is focused on exploring the capabilities that additive manufacturing presents, and is doing so via the EXMAN and EXFAB trailers, the Marine Maker Movement, and the dispersion of Nibbler drone capabilities. The EXMAN trailer at 1st Maintenance Battalion is leading the innovation effort within the Marine Corps. Second Maintenance Battalion recently fielded the EXFAB trailer, and is also beginning to explore how additive manufacturing can provide maintenance solutions for supported units. The Marine Corps is integrating the Nibbler in order to leverage the flexibility that its customizable printing can bring to any mission.

B. SUMMARY OF ANALYSIS

The CBA developed in this study showed that in a direct comparison, a CLIP machine (Carbon 3D’s M2) results in more total benefits, in 2017 dollars, to the Marine Corps than a Fortus 250mc. The analysis subjected the results to sensitivity testing to ensure validity of findings. The input variables tested included valuation of time and amount of DDL. While the net present values fluctuated as the metrics changed, CLIP remained the superior option. The metrics sensitivity analysis was intentionally set to the lowest plausible valuation to show a “worst case” scenario. The dramatic reduction in benefits reflects this change. A separate analysis monetarily equalized the initial investments, for a more accurate comparison. This part of the sensitivity analysis compared a single CLIP machine with two Fortus 250mcs. In this instance, the Fortus 250mcs provided more monetized benefits to the Marine Corps. Table 18 provides a summary of the results from each individual CBA and sensitivity evaluation.

Table 18. Summary of CBA and Sensitivity Evaluation

Method	Extrusion	CLIP
Baseline	$9,697,267.59	$15,470,288.11
Sensitivity of Value of Time	$4,037,667.94	$6,414,928.67
Sensitivity of DDL	$3,294,203.40	$5,225,385.41
Equalization of Initial Investment	$19,394,535.17	$15,470,288.11

As shown in Table 18, in all situations comparing single machines, CLIP retained the advantage. Only when the Fortus held a two to one count advantage did it lead on total NPV. Of note, doubling the Fortus machines only equates to a 25% increase in NPV compared to a single Carbon machine.

At the time of this study, the Marine Corps had approved the purchase of a Fortus 450 in addition to the currently utilized Fortus 250mc (D. Bower, personal communication, September 21, 2017). The purchase price is $145,000.00, equating to slightly more than a three-year service contract for a single M2 when discounted over three years. As the Fortus 450 is not yet in use, the associated print data and metrics are not available for analysis.

When comparing the advantages gained by leveraging one form of additive manufacturing over another, the intangibles play a critical role. Speed of printing is by far the largest concern as it has the most drastic impact on NPV. The durability and deployability of the machines and their respective print materials are also crucial. The M2 has the ability to print in Rigid Polyurethane (RPU), which produces a more durable finished product with higher tensile strength than the ABS available to the Fortus 250mc. The Fortus 450 brings the advantage of ultem, which is far superior to ABS in tensile strength, however is very rigid. This rigidity is more apparent when compared to RPU.

Leveling requirements are a concern for both machines in forward deployed locations. The size of the printers is also a factor when considering the current housing of the EXMAN and EXFAB trailers. While roughly the same physical size, in order to leverage the higher NPV of the Fortus 250mc, additional space is required for two printers vice a single M2. There are additional benefits realized through a service contract. Consistent maintenance is a critical asset. In the event of catastrophic failure, the company will provide a new machine. Additionally, a service contract model ensures that the Marine Corps always has access to the most efficient technology available. Considering the bottom line of the NPV along with the sum of these intangibles, Carbon 3d's M2 provides more benefit for the Marine Corps if utilized at full capacity.

C. RECOMMENDATIONS

Based on the analysis, data, and assumptions used in this research, and given that the Marine Corps is willing to embrace new technology, we recommend prudency in making sweeping changes with printers at this time. The following are three recommendations we formulate for the Marine Corps moving forward:

- Build a data repository of (block-chained) printable files as quickly as accuracy allows.
- Continue to use the Fortus 250mc and other previously purchased models.
- Once the repository outgrows the capability of the Fortus machines, move to Carbon 3D or a similar technology and expand the capability across the Marine Corps.

1. Recommendation Number One (Data Repository)

Building a data repository of printable files as quickly as possible is the key for the future of additive manufacturing within the Marine Corps and the DOD. The Marine Corps is incapable of fully utilizing any new printers due to the lack of requirements with printable parts. Everything done so far by 1st Maintenance Battalion has been exploratory in nature. They are answering the question of what additive manufacturing can really do for the Marine Corps. The answer to that question so far has been exceptionally positive. Additive manufacturing allows for a more effective supply chain, and the Marines at that unit have produced truly innovate solutions to maintenance issues. There is tremendous value in what they are doing.

The Marine Corps has not yet committed to systematically building a data repository. However, there has been tangible direction from DC I&L. In September 2017, DC I&L tasked 1st Maintenance Battalion with creating STL files for a list of 100 items (C. Wood, personal communication, September 22, 2017). The deadline for this task is March 2018. This is a step in the right direction; however, additional efforts are necessary. The Marine Corps can build a data repository internally, externally, or through a combination. Part of this decision-making process has to include an upgrade in scanners. Nikon has substantially invested in Carbon 3D, partially by providing a number of Nikon MCT225 technologically advanced scanners. These are capable of scanning an item in 30 minutes to five hours and automatically creating an STL file (J. Rolland, personal communication, October 4, 2017). The cost of operating this scanner is $480 per hour, if used on a per item basis (J. Rolland, personal communication, October 4, 2017). Further market research is necessary to determine if there are other similar capabilities available to the Marine Corps.

The CBA shows that the value of time warrants the change from an exploratory approach to a production approach. The break-even point for the Fortus 250mc is 15 parts over the life of the printer. This is assuming those parts bring a MCBul 3000 item from a deadlined status to a ready status. For the Carbon machines, the break-even point is 16 parts per year (48 parts over the life of the printer), operating under the same assumptions. To realize the full benefits of the machines as outlined by the CBA, the Fortus machines need to print 3.0 parts per day and the Carbon machines need to print 4.8 parts per day. Until utilizing the printers at their maximum capacity, there is no reason to invest in additional printers. Furthermore, any printers that the Marine Corps currently possesses and utilizes below these rates are operating below capacity.

2. Recommendation Number Two (Continue to Utilize Fortus 250mc)

Given the lack of a data repository, the advantages presented by the Carbon 3D machines are minimal. The allure of printing in RPU is important in a production model, but not in an exploratory model. Printing at less than full capacity diminishes the speed potential Carbon 3D machines offer. For now, there is no incentive to switch to the more capable M2.

The tipping point for this change is a full capacity workload for the Fortus 250mc. The Fortus 250mc can print 1,095 parts per year assuming a 12-hour workday. The required size of the data repository would depend on part usage rates (as reported by the SMU). A hypothetical data repository of 1,000 items allows the Fortus 250mc to print 10% of parts twice annually. As the requirement to print the same item multiple times increases, the size of the required data repository decreases. An aggressive and systematic approach of scanning and creating data files for the SMU's 500-1,000 most ordered NSNs is likely to exceed the threshold needed to increase print capabilities. At this point, the Marine Corps should begin purchasing the more advanced Carbon 3D printers.

3. Recommendation Number Three (Switch to CLIP and Expand Capabilities)

Once the data repository exceeds the capability of a single Fortus 250mc, the Marine Corps should switch to Carbon 3D or a similar technology if the market has expanded to allow competition. The Fortus 250mc is not capable of printing products in RPU or other high-quality materials. RPU is stronger than the ABS used by the Fortus 250mc and provides more flexibility than the ultem used by the Fortus 450 (Carbon 3D, 2017). Additionally, the Fortus 450 is an Extrusion printer. Despite the lack of available data, it is unlikely to print as quickly as the M2.

With the data repository in place, expand the printing capabilities across the Marine Corps to provide additive manufacturing solutions at every major base and station. This would include machines at the SMUs, maintenance battalions, and MEUs. In the event that the base or station does not possess one of these units, place the printer with the largest resident logistics unit. Carbon 3D stated that a full commitment to their company, designated as a service contract for 50 machines ($7.5 million pre-negotiation), would include the use of a Nikon scanner without additional charge (P. DeSimone, personal communication, September 14, 2017). The Marine Corps is currently not able to effectively utilize a service contract of this magnitude. However, once the data repository is in place a service contract could be beneficial, especially if the contract included scanning services. These scanning services would dramatically increase the size of the data repository making the services offered more effective day by day.

These recommendations continually reference Carbon 3D. However, it is important to note that the capability they currently possess may not be unique by the time the Marine Corps expands to production-level additive manufacturing. Any contract undertaken must account for scanning, print speed, material strength, deployability, and utilize a trade-off approach.

D. AREAS FOR FURTHER RESEARCH

This thesis built upon previous research conducted in the same field. Specifically, the work done by Matthew Friedell (2016) and Luke McLearen (2015) covered in the "Literature Review." This thesis explicitly addressed an area of future research identified by McLearen. At the completion of this thesis, there are four major areas requiring significant additional research.

1. What is the most efficient means of achieving a data repository?

Any data repository created must account for a myriad of factors including but not limited to the following:

- Intellectual property rights
- Consistent and secure reproducibility
- Ease of access
- Joint interoperability (to include DLA)
- Cost efficiency
- Efficient and systematic approach

A deficiency in any of these areas would create more problems than benefits for the Marine Corps. The Marine Corps is addressing several of these issues independently.

For example, consistent and secure reproducibility is a concern at multiple levels within the Marine Corps. SPAWAR and DC I&L are hopeful that block and chain is the solution for this facet of the larger issue. However, a holistic approach is required for a data repository, and that work is currently incomplete.

2. What percentage of NSNs at the SMU can be 3D printed?

Each respective SMU maintains an extensive on-hand stock, referred to as the General Accounts Balance File (GABF) using legacy terminology. A portion of these parts can be 3D printed (to include metal printing); the exact size of this portion is unknown. Every printable part would reduce expenditures and increase available warehouse space within the SMU. Understanding this situation will force decision makers to determine what to do with the SMU's budget and warehouse space. There are several readily apparent options:

- Continue to fund the SMU as usual and purchase additional parts that cannot be 3D printed to strengthen the supply chain.
- Continue to fund the SMU as usual and task them with maintaining and expanding the additive manufacturing capability.
- Use the funds to purchase additional secondary repairable items to strengthen the field level of maintenance.

It is important to determine the maximum amount of printable parts resident at the SMU. This amount is the desired endstate of additive manufacturing capabilities within the Marine Corps. Any parts produced beyond this point will not require mass reproduction. The work of 1st Maintenance Battalion and similar units will continue to advance this line of effort. However, the systematic production approach will be complete at this hypothetical point. The lack of a suitable model with statistical data limits is preventing the Marine Corps from effectively forecasting the amount of effort production level 3D printing will require.

3. What other CRADAs are possible and appropriate for the Marine Corps in the field of additive manufacturing?

The Marine Corps, via SPAWAR, has a CRADA in place with Methods 3D. This is currently being expanded to allow Methods 3D to print tank impeller fans in metal. The Marine Corps does not possess a complete picture of outsourcing needs for additive manufacturing, specifically who should be doing the work or research. DARPA has completed several projects related to additive and open manufacturing (Ford, Housel, & Mun, 2017). Additionally, other services within the DOD are actively pursuing this technology. The disparate nature of these lines of effort is most apparent at the lowest levels. There are no effective mechanisms in place for Marine Corps units exploring additive manufacturing to internalize lessons and challenges from sister services. The vertical and hierarchical approach is inefficient. This effort operates in an inherently network system. The Marine Corps requires thoughtful analysis and directives to move forward with new CRADAs.

4. How does the Marine Corps actually value time and does 3D printing improve a non-bottleneck?

This analysis presented multiple valuations of time. In spite of this, the valuation of time saved for maintenance warrants a separate research project. Supply chain management is specific about improving a non-bottleneck. If the Marine Corps does not realize the efficiencies gained by producing parts, they are worthless. Is the issue truly with the supply system or are there not enough mechanics to make repairs? With the advent of armored vehicles, the mechanic-to-equipment ratios have changed in some situations. The end items with armor are simply too heavy for one person to safely repair on his or her own. Major Aaron Glover (USMC) is currently researching the optimal mechanic-to-equipment ratios for the Marine Corps. Future research can answer the question using this thesis, Glover's work, and original research.

LIST OF REFERENCES

3D printers start to build factories of the future. (2017). *The Economist.* Retrieved from https://www.economist.com/news/briefing/21724368-recent-advances-make-3d-printing-powerful-competitor-conventional-mass-production-3d

3D Systems. (2017a). Spine mentor. Retrieved from https://simbionix.com/simulators/spine-mentor/

3D Systems. (2017b). Spine mentor features and benefits. Retrieved from https://simbionix.com/simulators/spine-mentor/spine-mentor-features-and-benefits/

Additively Ltd. (n.d.). Material jetting. Retrieved from https://www.additively.com/en/learn-about/material-jetting

Aerojet Rocketdyne. (2015, March 16). Aerojet Rocketdyne hot-fire tests additive manufactured components for the AR1 engine to maintain 2019 delivery. Retrieved from http://www.rocket.com/article/aerojet-rocketdyne-hot-fire-tests-additive-manufactured-components-ar1-engine-maintain-2019

AET Labs. (2017). *Fortus 250mc material cartridges* [Fact Sheet]. Retrieved from aetlabs.com/product/p430-5-pack-340-2120f-model-material-fortus-250mc/

Appleton, R. (2017). *Additive manufacturing overview for the United States Marine Corps*. Sterling Heights, MI: RW Appleton and Company.

Apis Cor. (2017). The first on-site house has been printed in Russia. Retrieved from http://apis-cor.com/en/about/news/first-house

AS Logistics. (2016). Retrograde logistics. Retrieved from https://asl-af.com/afghanistan/retrograde-logistics/

Benedict. (2017, August 21). New Congress-approved defense bill could mean more military contracts for 3D printing companies. *3ders.org*. Retrieved from http://www.3ders.org/articles/20170821-new-congress-approved-defense-bill-could-mean-more-military-contracts-for-3d-printing-companies.html

Boardman, A., Greenberg, D., Vining, A., & Weimer, D. (2011). *Cost-benefit analysis concepts and practice*. Upper Saddle River, NJ: Prentice Hall.

Burton, J., Wang, S., Behringer, R., & Larina, I., (2016, March 9). *Three-dimensional imaging of the developing mouse female reproductive organs with optical coherence tomography.* Presentation at the Society of Photo-Optical Instrumentation Engineers (SPIE). http://dx.doi.org/10.1117/12.2213202

Carbon 3D. (n.d.). Our process. Retrieved from https://www.carbon3D.com/clip-process

Carbon 3D. (2017). Rigid polyurethane. Retrieved from https://www.carbon3d.com materials/rpu-rigid-polyurethane/

Crawford, M. (2016). New technology transforms 3D printing. Retrieved from https://www.asme.org/engineering-topics/articles/manufacturing-design/new-clip-technology-transforms-3D-printing

Defense Federal Acquisition Regulation Supplement (DFARS), 48 C.F.R. ch. 2 (2016). Retrieved from http://farsite.hill.af.mil/vfdfara.htm

Defense Systems Information Analysis Center (DSIAC). (2016, December 16). DOD releases additive manufacturing roadmap. Retrieved from https://www.dsiac.org/resources/news/dod-releases-additive-manufacturing-roadmap

Department of Defense, Inspector General (DOD IG). (2010, June 17). *Government oversight of field services representative and instructor services in support of the mine resistant ambush protected vehicle program* (Report Number D-2010-068). Arlington, VA: Author.

DeSimone, J. (2015, March). *What if 3D printing was 100x faster* [Video file]. Retrieved from https://www.ted.com/talks/joe_desimone_what_if_3d_printing_ was_25x _ faster

Desktop Metal. (2017). An end-to-end solution. Retrieved from https://www.desktopmetal.com/products/studio/

Erwin, S. (2017, May 8). Marines take 3D printed drones from the lab to the field. *Defense Systems*. Retrieved from https://defensesystems.com/articles/2017/ 05/08/marinecorpprint.aspx

Fallows, J. (2016, June 18). More on the public role in fostering private innovation. *The Atlantic Online*. Retrieved from https://www.theatlantic.com/notes/all/2016/ 06/does-the-maker-movement-matter/486647/

Federal Acquisition Regulations (FAR), 48 C.F.R. ch. 1 (2005). Retrieved from https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf

Ford, D., Housel, T., & Mun, J. (2017). *Shrinking the "mountain of metal": The potential of three advanced technologies.* Paper presented at the 14th Annual Acquisition Research Symposium, Monterey, CA.

Friedell, M., (2016, June). *Additive manufacturing (AM) in expeditionary operations: Current needs, technical challenges, and opportunities* (Master's thesis, Naval Postgraduate School). Retrieved from http://www.dtic.mil/docs/citations/AD1026571

General Electric. (2016). Letter to shareholders, leading the digital industrial future. Retrieved from http://www.ge.com/ar2016/ceo-letter/beyond/

Government Accountability Office (GAO). (2009, March). *GAO cost estimating and assessment guide: Best practices for developing and managing capital program costs*. (GAO-09-3SP). Washington, DC: Author.

Government Accountability Office (GAO), (2015, October). *Defense additive manufacturing: DOD needs to systematically track department-wide 3D printing efforts* (GAO-16-56). Washington, DC: Author.

Grimm, T. (2004). *User's guide to rapid prototyping*. Dearborn, MI: Society of Manufacturing Engineers.

Harper, J. (2015, November) Military 3D printing projects face challenges. *National Defense Magazine*. Retrieved from http://www.nationaldefensemagazine.org/articles/ 2015/11/1/2015november-military-3d-printing-projects-face-challenges

Heater, B. (2016). Stratasys debuts new 3D printing tech partnerships with Ford and Boeing. *Tech Crunch*. Retrieved from https://techcrunch.com/2016/08/24/ Stratasys

Iansiti, M., & Lakhani, K. (2017, January–February). The truth about blockchain. *Harvard Business Review*. Retrieved from https://hbr.org/2017/01/the-truth-about-blockchain

Jackson, T. (2017, July 20). Navy partnership goes to new depths with first 3D-printed submersible. Washington, DC: Office of Energy Efficiency & Renewable Energy. Retrieved from https://energy.gov/eere/articles/navy-partnership-goes-new-depths-first-3d-printed-submersible

Joyce, J., Louis, M., & Seymour, T. (2014, November 20). 3D opportunity for the Department of Defense. *Deloitte Insights*. Retrieved from https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/additive-manufacturing-defense-3d-printing.html

Kirkman, M., Ahmed, M., Albert, A., Wilson, M., Nandi, D., & Sevdalis, N. (2014, August). The use of simulation in neurosurgical education and training a systematic review. *Journal of Neurosurgery, 121*(2), 228–246. Retrieved from http://thejns.org/doi/full/10.3171/2014.5.JNS131766

Kornei, K. (2017, May 16). 3D-printed ovaries restore fertility in mice. *Science Magazine*. Retrieved from http://www.sciencemag.org/news/2017/05/3D-printed-ovaries-restore-fertility-mice

Locker, A. (2017). Metal 3D printer guide 2017—All about metal 3D printing. Retrieved from All3DP website: https://all3dp.com/metal-3d-printer-guide/#The%20 Printers

Loughborough University. (2017a). Binder jetting. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binder jetting/

Loughborough University. (2017b). Directed energy deposition. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

Loughborough University. (2017c). Material Extrusion. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/material Extrusion/

Loughborough University. (2017d). Powder bed fusions. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

Loughborough University. (2017e). Sheet lamination. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheet lamination/

Loughborough University. (2017f). VAT photopolymerzation. Retrieved from http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/

Malaty, E., & Rostama, G. (2017, February). 3D printing and IP law. *World Intellectual Property Organization (WIPO) Magazine*. Retrieved from http://www.wipo.int/wipo_magazine/en/2017/01/article_0006.html

Marks, G. (2017, March 7). This start-up will 3D print your house … for $10K. *Washington Post*. Retrieved from https://www.washingtonpost.com/news/on-small-business/wp/2017/03/07/this-start-up-will-3d-print-your-house-for-10k

Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research, 5*(1), 30–39. Retrieved from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1099&context=jpeer

McLearen, L., (2015, June). *Additive manufacturing in the Marine Corps* (Master's thesis, Naval Postgraduate School). Retrieved from http://www.dtic.mil/docs/citations/ ADA632451

Millsaps, B. (2017, August 21). U.S. Army forges ahead in their commitment to 3D printing. Retrieved from https://3dprint.com/184828/army-commitment-to-3d-printing/

Mims, C. (2017, May 15). 3-D printing is taking its next step: Your shoes. *The Wall Street Journal*, pp. B1, B4.

Mizokami, K. (2017, March 8). The U.S. Army 3D-printed a grenade launcher and called it R.A.M.B.O. *Popular Mechanics*. Retrieved from http://www.popularmechanics.com/military/weapons/advice/a25592/the-us-army-3d-printed-a-grenade-launcher-it-calls-rambo/

Morris, A. (2016, January 11). A new way to print 3-D metals and alloys. Evanston, IL: Northwestern University, McCormick School of Engineering. Retrieved from http://www.mccormick.northwestern.edu/news/articles/2016/01/a-new-way-to-print-3-d-metals-and-alloys.html

Morrow, A. (2017, January), The Corps challenges Marines to make their future. Washington, DC: Office of the Secretary of the Navy. Retrieved from www.secnav.navy.mil/innovation/Documents/2017/01/MarineMaker.pdf

Muniz, B., & Peters, K. (2016). *An analysis of additive manufacturing production problems and solutions* (Master's thesis, Naval Postgraduate School). Retrieved from https://calhoun.nps.edu/bitstream/handle/10945/51589/16Dec_Muniz_Peters.pdf?sequence=1

Newman, J. (2017, June 8). Hitting print: Navy on board with additive manufacturing. *Naval Aviation News*. Retrieved from http://navalaviationnews.navylive.dodlive.mil/2017/06/08/hitting-print-navy-on-board-with-additive-manufacturing/

NewPro 3D. (2016a). Comparison speed test. Retrieved from http://www.newpro 3D.com

NewPro 3D. (2016b). ILI technology. Retrieved from http://www.newpro3D.com/ili-technology/

NSN Center. (2017). *What is NSN?* [Fact sheet]. Retrieved from https://www.nsn center.com/Tutorials/NSNDefinition

Office of Manpower and Budget (OMB). (1992). *Guidelines and discount rates for benefit-cost analysis of federal programs* (Circular A-94). Washington, DC: Author. Retrieved from https://www.transportation.gov/regulations/omb-circular-94

Office of the Chief of Naval Operations (CNO), (2015, September 3). *Additive manufacturing/3-D printing* [Memorandum]. Washington, DC: Author.

Optomec. (2017). Aerosol jet technology for 3D printed electronics. Retrieved from http://www.optomec.com/printed-electronics/aerosol-jet-technology/

Ostroska, J. (2014). Commandant of Marine Corps awards Afghanistan unit. Retrieved from http://www.military.com/daily-news/2014/ 02/26/commandant-of-marine-corps-awards-afghanistan-unit.html

Perrin, A. (2017, January 30). Army's additive manufacturing roadmap merged into DOD's. Retrieved from https://www.army.mil/article/ 81551/armys_additive_manufacturing_roadmap_merged_into_dods

Ponoroff, L. (2017). 3D Systems releases Simbionix SPINE mentor simulator for spine surgeries. Retrieved from https://www.healthcaretrainingandeducation.com/ surgical/3D-systems-releases-simbionix-spine-mentor-simulator-spine-surgeries/

Sample, I. (2017, May 16). 3D-printed ovaries allow infertile mice to give birth. *The Guardian*. Retrieved from https://www.theguardian.com/science/2017/may/16/3d-printed-ovaries-allow-infertile-mice-to-give-birth

Schneider, T. (2017, May 15). DOD believes blockchain can boost 3-D printing at the front. *GCN*. Retrieved from https://gcn.com/Articles/2017/05/15/DOD-blockchain-3D-printing.aspx

Securities and Exchange Commission (SEC). (2016). Notice of exempt offering of securities (SEC FORM D/A: OMB Number 3235-0076). Retrieved from https://www.sec.gov/Archives/edgar/data/1648978/000164897816000002/xslForm DX01/primary_doc.xml

Takano, M. (2016, March 17). What do we do with these empty Wal-Marts? Retrieved from https://medium.com/a-nation-of-makers/what-do-we-do-with-these-empty-wal-marts-27ab1f576f2c

Tampi, T. (2015, June 25). Smartech report: 3D printing in dental market to reach $3.1 billion by 2020. Retrieved from https://3dprinting industry.com/news/smartech-report-3d-printing-in-dental-market-to-reach-3-1-

Tepper, F. (2017, April 7). Adidas' latest 3D-printed shoe put mass production within sight. *Tech Crunch.* Retrieved from https://techcrunch.com/2017/04/07/adidas-latest-3D-printed-shoe-puts-mass-production-within-sight/

Trounson, A. (2017, August 22). *Five ways 3D printing is changing medicine.* Retrieved from https://pursuit.unimelb.edu.au/article /five-ways-3d-printing-is-changing-medicine

Under Secretary of Defense for Acquisition, Technology, and Logistics (USD [AT&L]). (2001, October 15). *Intellectual property: Navigating through commercial waters*. Washington, DC: Author.

United States Army. (2013). *U.S. Army cost benefit analysis guide, 3rd ed. (V3.1)*. Washington, DC: Office of the Deputy Assistant Secretary of the Army (Cost and Economics).

United States Marine Corps. (2001). *Marine Corps operations* (Marine Corps Doctrine Publication [MCDP] 1–0). Washington, DC: Author.

United States Marine Corps. (2016a, January). *Fragmentary order 01/2016: Advance to contact*. Washington, DC: Headquarters Marine Corps, Office of the Commandant.

United States Marine Corps. (2016b, September 16). (Maradmin 489/16). Retrieved from http://www.marines.mil/News/Messages/MARADMINS/Article/946720/ interim-policy-on-the-use-of-additive-manufacturing-3d-printing-in-the-marine-c/

United States Marine Corps. (2017a). Core focus areas. Marine Corps Installation and Logistics. Retrieved from http://www.iandl.marines.mil/Divisions/Logistics PlansPoliciesStrategicMobility(LP)/LogisticsVisionandStrategyBranch(LPV)/LPV-3Homepage.aspx

United States Marine Corps. (2017b). *Exercise Steel Knight 2017 (SK17) after action report.* Combat Logistics Regiment 1. Camp Pendleton, CA: 1st Marine Logistics Group.

United States Marine Corps. (2017c). *Marine Corps operations and readiness* (Marine Corps Bulletin [MCBul] 3000). Washington, DC: Author.

United States Marine Corps. (2017d). Strength in adaptability. *Marine Maker*. Retrieved from https://www.md5.net/marinemaker

Van Dussen, M. (2017, June 19). Mad props: A 3-D printed airplane engine will run this year. *GE Report*. Retrieved from http://www.gereports.com/mad-props-3D-printed-airplane-engine-will-run-year/

Wohlers, T., Campbell, I., Diegel, O., Kowen, J., & Caffrey, T. (2017). *Wohlers report 2017: 3D printing and additive manufacturing state of the industry annual worldwide progress report.* Fort Collins, CO: Wohlers Associates.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California